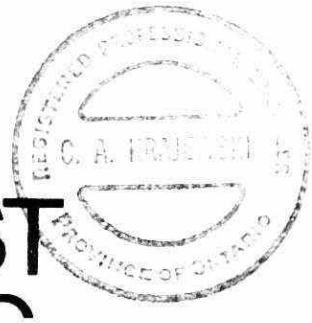

QUARRY BLAST ATMOSPHERIC WAVE (CONCUSSION) RESPONSE OF STRUCTURES AND HUMAN ANNOYANCE

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Ontario Ministry of the Environment

The Honourable
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Minister

Everett Biggs,
Deputy Minister

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QUARRY BLAST ATMOSPHERIC WAVE (CONCUSSION)

RESPONSE OF STRUCTURES AND HUMAN ANNOYANCE

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ABSTRACT

A series of quarry blasts was monitored to determine if the acoustic wave was likely to be of significance from the points of view of structural damage and human annoyance.

The characteristics of the blast wave, overpressure, spectrum and duration were studied and compared with the characteristics of sonic booms.

The relative significance of ground vibration and airblast were studied and simultaneous vibration and overpressure measurements taken.

The two phenomena were shown to be similar in spectral content. The overpressure at several thousand feet from a blast can be similar to that of a sonic boom and the duration of the pressure pertubation is several times longer for a blast than for a sonic boom.

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1. INTRODUCTION

Quarry operators and government agencies have for many years received complaints from residents around quarries. These complaints often claim that the blasting at the quarry is causing damage to their houses or that it shakes windows and causes articles on shelves to move.

Ground vibration measurements have usually proved to be very low and some observers believe that the airblast or "concussion" is the real source of annoyance.

Several reports on airblast from explosives suggest a threshold of damage at 1 - 2 psi overpressure. However many recent studies on the sonic booms produced by supersonic aircraft indicate a threshold of damage two orders of magnitude lower. This report therefore attempts to answer the following questions:

Is the overpressure produced by a quarry blast high enough to cause structural excitation, a) to the point of damage and b) to the point of annoyance, in the area around a quarry?

Are there circumstances under which the air blast can be more significant than the ground vibration, from structural and annoyance points of view?

Are the spectral contents of airblasts and sonic booms sufficiently similar that annoyance and damage criteria derived from the sonic boom studies may be applied to blasts?

What is a suitable way to monitor airblasts on a routine basis? Some blasting consultants do measure sound pressure level using "C" or "A" scale weightings which may be unsuitable in this application.

This study made use of instrumentation developed for sonic boom measurement, capable of measuring pressure variations at very low frequencies in addition to the normal audio range. This was used to monitor a series of normal quarry blasting operations in a variety of locations.

2. OTHER STUDIES

2.1.1 Structural Response due to Airblast

In 1942 Windes (1) carried out a detailed study to determine the characteristics of the airblast produced by blasting at quarry operations. This involved monitoring actual quarry blasts of various types and experiments on window damage due to open air explosions of single sticks of dynamite. Windes' major conclusions, for the blast wave were:-

(i) Propagation was 1125 feet/sec at 70°F which is approximately the speed of sound.

(ii) The peak overpressure attenuates at a greater rate than the inverse square law for intensity would suggest.

(iii) Doubling the charge weight will increase the peak overpressure by approximately 50%.

(iv) Reflections and directional effects are very significant for open air shots.

The conclusions from the damage studies showed that for one stick of dynamite exploded in the air, damage starts at 1 - 2 psi. From these results and monitored quarry blasts it was considered that under normal operating conditions the problem of damage from airblast was insignificant.

Nicholls, Johnson and Duvall (2) enlarged on this subject, taking overpressure measurements for various scaled distances and scaled depths at several quarry blasting sites. From these results, Windes previous study and from studies conducted by the Ballistic Research Labs (Fig. 1), Nicholls et al recommended a safe limit on blast overpressure of .5 psi (72 psf). It was considered that such a value would adequately take into account possible focusing due to temperature inversion and/or adverse wind velocity gradients.

Edwards and Northwood (3) carried out a series of tests to the point of damage of several structures which were to be removed because of the St. Lawrence Power Project. In order to preclude damage from airblast, overpressure was monitored throughout the study. The system

employed a crystal microphone in conjunction with a cathode ray oscilloscope and the resulting signature was photographed. The frequency response of the system was 20 - 7, 500 Hz. The measurements taken with this system are shown in Table 1.

Three major studies to determine the community response to sonic boom have been carried out in the United States. The USAF - NASA and FAA conducted a series of supersonic overflights over populated areas and detailed records were kept of maximum overpressures, damage claims, complaints etc. In 1961-1962 the population of St. Louis Missouri was exposed to 150 sonic booms over a 10 month period resulting in 390 million "Boom Person Exposures", (BPE), (4),(5). In 1964 Oklahoma City (6) was subjected to 1253 sonic booms resulting in 642 million BPE over a 26 week period and in 1965 a similar study was conducted in Chicago with 49 booms and 304.5 million BPE. The damage data from these tests is summarized in Table 2. From the St. Louis study it was concluded that incipient damage occured at overpressures of 2.0 - 3.0 psf all superficial in nature consisting mostly of cracks in brittle surfaces. The breakdown of the type of damage was: Glass only, 37%, Plaster only, 22%, Glass and Plaster, 11%, Bric A Brac, 18.5%, tiles and fixtures, 7.5%, other structural damage 4%. (7)

Monitored buildings in the Oklahoma City study showed no damage for nominal overpressure as high as 6 psf and vibrational accelerations and displacements were of the same order as produced by slamming doors and walking.

C.H.E. Warren (8) performed tests on 30 greenhouses of various types using simulated sonic booms produced by line charges. Table 3 shows damage occuring as low as 1.0 psf overpressure. The table is cumulative, that is the overpressure was steadily increased so that the weakest, poorest set windows failed first and the strongest windows did not break at all within the range produced, i.e. to 4.2 psf. In all, 239 out of the 35,000 panes broke during this experiment, i.e. about .7%.

Warren also predicts (Table 4 & 5) the vibration response of cathedral structures due to sonic boom of about 2.5 psf. These were calculated after tests on two German churches using small explosive

charges and indicates significant vibration, especially for roofs and windows. Although such levels would not cause instantaneous damage, Warren notes that repeated exposures might fatigue structures.

Early experience at the Building Research Station, Herts, England, measuring bomb and gun blasts had shown a damage threshold of 1 - 2 psi as did Windes (1) but reports of sonic boom induced damage at overpressures 2 orders of magnitude lower prompted study. Newberry (9), instrumented two structures, one fairly old but in good condition and another small new structure. Accelerometers and shock pressure gauges were mounted on the ground and on the structure. Tables 6,7,8 show overpressure and vibration results for 5 overflights by RAE experimental aircraft. Acceleration levels in Table 8 reach 1.0 g, which some North American jurisdictions use as criterion for the threshold of damage. The threshold of damage was therefore reached in this experiment for overpressures not greater than 5 psf.

Mayes and Edge (10) compared structural response due to sonic booms, explosives and a rocket engine. The relative signatures are shown in Figure 2 and the relative strains in Figure 3. The strains were measured in a vertical stud and the corresponding stress vs. overpressure relationship is shown in Figure 4. Mayes & Edge concluded that damage to primary structures was unlikely at the overpressures measured and that stresses due to explosives were lower than for booms of the same peak overpressure. Mayes & Edge considered this to be due to the double shock of a sonic boom being in phase with a natural structural mode whereas the explosive produced only one shock. Further tests on a 3' x 3' window showed no damage at overpressures less than 20 psf.

2.1.2 Human Annoyance

There is little published work to date on the annoyance effects of blasting. However the extensive work done on sonic booms and to a lesser extent on artillery noise, gives some insight to the problem.

Kryter & Pearsons (11,12) made comparisons between the subjective responses to sonic booms and subsonic jets noise as heard indoors. Table 9 indicates the pressure attenuation which can be expected and also indicates the considerable effect of secondary noise sources such as rattling of windows, crockery, etc. Kryter notes that frequency components below 20 Hz contribute to perceived noisiness or "unwantedness" of the boom if not to the loudness and that calculated PNdB levels for sonic booms exceeds PNdB values of subsonic jets when judged to be equally noisy even if the calculation for booms includes contributions down to 1 Hz. The difference is 12 PNdB and was judged to be due to the large difference in duration, 12 sec. for the jet and 200 msec for the boom. Kryter demonstrated some adaptation in startle effect after repeated exposure as measured by heart rate. However in questionaires some of the subjects indicated startle even when there was no change in heart rate.

Broadbent & Robinson (13) showed by comparison with jet and piston aircraft noise that the upper limit of acceptable sonic boom overpressure (heard indoors) is about 1.9 lb/ft^2 measured outdoors. This figure is based on the value of 110 PNdB as being the sound level considered the maximum acceptable for conventional aircraft. The equipment used in this experiment had the deficiency that no sound below 30 Hz was produced although the maximum energy is normally well below this frequency, in the infrasonic range.

In the St. Louis community study referred to above (4), the population were subjected to 40 sonic booms over the initial 4 month period of the tests using B-58 &F106 aircraft. Thirteen additional flights were made over the same area at various times of day and night over the next six months and four special flights were flown with increased boom overpressures. One thousand, forty-three people were interviewed after the first series of booms and after the special flights.

Table 10 summarizes the range of overpressures measured over the study area as a function of distance from the ground track of the aircraft and Table 11 indicates the responses of the people

interviewed. Although the majority of people expressed concern primarily about safety to their property, as is the case with quarry blasts, nevertheless the overpressure threshold of damage was clearly an exposure level unacceptable to the population. Table 12 indicates the predicted effects and reactions. Nixon & Borsky concluded that booms experienced indoors were subjectively worse than those heard outdoors because of longer duration and the associated rattling of household items. Nixon & Borsky also concluded that overpressure alone was not a sufficient criterion for acceptability, that frequency of occurance and time of occurance, duration of the program and the particular signature of the boom are also very significant.

Von Gierke & Nixon (14) collected various of the studies carried out into one report. The importance of the boom signature referred to above is again indicated in Figure 5 which shows a very strong dependence of annoyance and loudness on the signature rise time and little if any dependence on duration. In addition to rise time, the effect of a "peaky" signature is shown in Figure 6 where the increment in relative loudness is considerably greater than the increment in overpressure. The Oklahoma City study (5,6,7,14) gave the dependence of public response as a function of overpressure shown in Figure 7. In this study 1253 sonic booms were produced at a maximum rate of 8/day and a median overpressure of 1.2 psf. Three interviews were conducted with each of the 3000 families during the six month program. This level of exposure is rather high compared with the normal rate of blasting at quarries but gives a useful conservative guide to likely public reaction.

In an intensive 1 month test at Edwards A.F.B. the community was subjected to 289 booms at a mean peak overpressure of 1.7 psf, Figure 8 (14), (15). This study indicated very few complaints at overpressures below 1 psf. However the Base community had been exposed to sonic booms of 4 to 8/day for over a year and may be more tolerant than other communities not associated with the military.

The importance of boom signature shape, ie. spectral content from the point of view of subjective level was emphasized by Warren (16).

Experiments trying to relate annoyance to overpressure for several types of short duration sound, sonic boom, burst of white noise, explosive bang or jet fly-over gave very little correlation because of the very different frequency content of these sounds. The following procedure was then used on these sounds in order to calculate loudness. A transient can be resolved into its Fourier components (Fourier transform of the pressure - time function).

(1) ie. $$F(\omega) = \int_{-\infty}^{\infty} p(t)\, e^{-j\omega t}\, dt = \int_{0}^{\tau} p(t)\, e^{-j\omega t}\, dt$$

τ = duration

Then the energy density spectrum is

(2) $$\Phi = 2\pi |F(\omega)|^2$$

This is then converted to a power density spectrum by dividing by T duration (about 100 ms)

(3) Hence SPL = $$10 \log_{10} \frac{\left(\frac{2\pi}{T} |F(\omega)|^2 \right)}{P_{ref}^2}$$

Where F is the sound pressure level due to a band of unit frequency width centered at circular frequency (ω).

Warren calculated the energy in the usual octave bands, i.e. summed equation (2) over the range of each octave band so that equation (3) represented the SPL in the octave band with centre frequency ω. Stevens MkVI equal loudness contours were then used with the addition of three octave bands extrapolated into the infra-sonic range. A correction was then made to account for the effect of short duration. Figure 9 shows the resulting correlation between annoyance and the calculated subjective level.

A further result of Warren's work of significance in this study is that explosive bangs of short duration but high overpressure

(10 psf) were not as intolerable when heard indoors as one might expect. Measurements showed that the loudness of the indoor event is roughly proportional to the impulse of the event as measured outdoors, ie. the area under the pressure time signature.

Thus we have the phenomenon that a short duration explosion with short rise time and high overpressure would be subjectively louder than an explosion of equal overpressure but longer rise time and duration when heard outdoors. However the same two explosions when heard indoors can be reversed in annoyance because the latter type would have the greater impulse, the high frequencies of the first type being attenuated due to the transmission loss of the residence wall.

It seems unlikely that a real trade-off situation exists with respect to blasting, ie. whether one could reduce the number of delays and thereby duration and impulse resulting in less annoyance to people indoors. Shortening the duration would not affect the relative spectrum much, if at all, so any trade-off would be purely duration and impulse for overpressure. In such case, the increase in overpressure would probably be more significant for annoyance than the decrease in impulse.

The effect of rise time specifically was demonstrated by Zepler & Harel (17) in laboratory tests on about 70 subjects who judged the comparative loudness of a 400 Hz tone and N waves applied to earphones. Figure 10 shows the relationship derived. It was also shown that filtering out the signal below 20 Hz or 40 Hz had little effect on subjective loudness. This of course does not take account of the feeling of being struck that the low frequency components cause, which Kryter (11) referred to as adding to the "unwantedness" if not the loudness of the boom. Zepler & Harel also demonstrated that the subjective loudness could be estimated from the Fourier components of the signal by a method differing slightly from that of Warren.

Schomer (18) developed a procedure for evaluating the likely community response due to training activities at U.S. military bases. The noise sources were artillery blasts with accompanying shock waves produced by supersonic shells and explosion of charges both above the ground and just below ground.

The method consisted first of estimating the peak sound level produced by the explosive (an equivalent amount of TNT) then calculating the perceived noise level (PNL) in PNdB, calculating the effective perceived noise level (EPNL) in EPNdB by estimating the duration of blast noise, adding Kryter's (19) impulse correction and finally by deriving the Composite Noise Rating (CNR) by knowing the frequency of occurances. The procedure for estimating peak overpressure is of particular interest here.

The peak SPL due to 1 lb. of TNT is estimated using the curve derived by the U.S. Naval Ordinance Lab (20) Figure 11. The equation of the NOL base curve is Po dB = 153 - 22.3 $\log_{10} \frac{D}{200}$ which implies an attenuation with distance greater than spherical spreading would accoun for as stated by Windes (1), (6.7 dB/doubling of distance rather than 6 dB for a point source). From this equation or from the graph, the base level Po is calculated. Focus factors due to temperature inversion and wind gradient are then applied to give probable or worst case forecasts. Schomer uses average focus factors based on B.R.L. and A.E.C. data in deriving maximum and probable focus overpressure curves, Figure 12.

2.2.1 Seismic Effects (Structural)

Undoubtedly seismic effects of blasting have had much more attention and measurement than acoustic effects. It is very common for quarries to retain on a long term basis the services of blasting consultants who either monitor blasts with their own equipment or interpret the results of measurements taken with the quarry's own seismometer. This is also done for construction blasting which can be much more critical because of the proximity to structures.

In the case of complaints from residents around quarries, the Ontario Ministry of Natural Resources often advises quarries to monitor the vibration as a safeguard. It is also a protection in case of damage claim where the generally recognized (though not in law) safe limit of 2.0 ins/sec. peak particle velocity is used as a guide.

One of the earliest and most substantial studies of seismic effects was carried out between 1935-1940 by Theonen & Windes (21). These researchers found that many of the seismometers used at that time tended to oscillate at their own natural frequency rather than the frequency of excitation and that it was often not known what parameter, displacement, velocity or acceleration was being measured. A special seismometer and calibrating table were constructed in 1935 to measure displacement directly. In 1937 a test was carried out at Mt. Weather, Va., where explosive was placed in an adit under a house and the charge increased until minor damage was caused. This site was chosen so that there existed no possibility of excitation due to air-blast. Plaster cracks appeared at displacements of 0.08 - 0.09 ins. Quarry blasts carried out in the same area gave considerably smaller displacements. In 1938-1939 the same researchers carried out tests on houses using a mechanical shaker from which the following conclusions were drawn.

(i) Vibration accelerations due to blasting which caused no damage corresponded to "severe" or "total" damage on the Mercalli earthquake scale implying that such a scale was totally inapplicable to blasting vibrations. (Earthquake vibrations are of much lower frequency).

(ii) There is a great deal of damping in housing structures so that the damage due to the excitation of structural resonances is most unlikely.

(iii) The acceleration due to gravity 1 g. is a useful guide to the threshold of structural damage (plaster cracks).

(iv) Normal quarry operations do not produce vibration severe enough to damage structures at normal distances.

Support for this last conclusion is shown in Table 13 (22) which compares vibrations in a house due to various normal activities. In the Edwards and Northwood study (3) displacements and to a lesser extent velocities were measured in the walls of structures for a series of explosions to the point of major damage. The measurements, Figure 13 and 14, plotted versus principal frequency component suggested a

correlation of damage with particle velocity and a damage threshold of about 4 inch/second. A safe limit of 2 inches/second was recommended.

A subsequent experiment carried out by Edwards, Northwood and Crawford (23) in connection with a hydro-electric project at Carillon Falls on the Ottawa River gave considerable support to the use of peak particle velocity as a damage criterion. Figures 15 and 16 show vibration results from six buildings, some on rock, some on glacial till which were subjected to blasts.

The houses ranged from 30 to 70 years old and the masonry and concrete labels refer to the type of basement structure. Edwards & Northwood concluded that for blasting in till and rock, longitudinal vibration velocity provided the best criterion for damage and that the threshold of damage in that particular terrain was about three inch/sec. Simultaneous strain gauge measurements suggest that the threshold of damage occured at about 40 μinches/inch but this was not conclusive.

The acceleration measurements indicate that although there is less correlation with damage, a criterion of 1 g as safe limit is reasonable, confirming the early work of Theonen & Windes.

An empirical law for use in controlling blast vibration levels where instrument data was not available was derived from this study, $\frac{E^{2/3}}{d} = 0.1$ where E is the charge weight in pounds and d the distance to the structure of concern. Where this formula is applied to multi-delay blasting it was recommended that an additional factor of safety of 2 be applied to the maximum charge/delay.

Langfors, Kihlström and Westerberg (2) performed a similar experiment to Edwards & Northwood on a construction project in Stockholm where both buildings and explosive charge were in rock. Figure 17 shows displacement versus frequency and two regression plots for minor and major damage calculated by Duvall & Folgelson (22). The hypothesis that these lines have slopes of (-1) ie. a velocity dependence was shown to be acceptable with a 90% confidence level. Langfors et al recommended a safe limit of 2.8 inch/second particle velocity.

Nicholls, Johnson and Duvall (2) carried out a comprehensive program of measurements to determine a propagation law for vibration from quarry blasting. The form of relationship was found to be

$$v = H \left(\frac{D}{W^{\frac{1}{2}}} \right)^{\beta}$$

Where v is a vector component of vibration velocity, D the distance, W charge weight and H & β constants for a particular site and velocity component (vertical, radial, transverse).

The recommended procedure is to determine the constants in the above equation by test explosions for the 3 components and then to choose a suitable maximum scaled distance to ensure a particle velocity of 2 inch/second will not be exceeded at the points of concern. In the absence of such experimental data, a minimum scaled distance of 50 feet/(pound)$^{\frac{1}{2}}$ was recommended. The velocity data from all the USBM studies is summarized in Figure 18. These plots can be used directly as a guide to safe blasting.

2.2.2 Seismic Effects (Annoyance)

Although some considerable work has been done on annoyance due to continuous vibration, very little has been written on annoyance due to an isolated impact type of vibration. For either type it is difficult to separate the subjective response due to the vibration from the response to the simultaneous sound. Investigations into annoyance due to "vibration" from subways in Toronto (24) shows an increase in sound level in adjacent homes due to trains of about 12 dBC while the vibration velocity level is about .02 inch/second; the approximate threshold of perception (25).

The author has investigated several noise-vibration problems due to impact machinery, where the energy is transmitted via the ground manifesting itself as low frequency air-borne sound inside a residence. In such cases the complaint was invariably referred to as vibration, although the vibration level measured proved to be in the region of, or well below the threshold of perception. The air-borne sound produced by such small movement in the floor and walls of the structure

can cause very high sound levels as well as exciting secondary noise sources such as windows and bric a brac. Figures 19, 20 (26) are examples of this type of phenomenon measured by the author.

These show the increase in sound level in residences due to impact machinery in nearby buildings. In both cases, the impact machinery was inaudible outside the buildings. The figures indicate the sound levels measured using a Bruel & Kjaer impulse sound level meter type 2204 in the usual octave bands. The vibration, acceleration level indicated in Figure 19 was just above the threshold of perception (27) and in Figure 20 velocity level was measured and found to be below the threshold of perception. In both cases the noise level was very disturbing.

The complaint history following an underground nuclear explosion near Hattiesburg, Mississippi is shown in Figure 21 (2) as a function of particle velocity. Based on this result more than 35% of people exposed to the generally accepted safe limit for structures find such a level intolerable.

No data is available on the simultaneous sound level.

A quarry blast, produces both air and ground vibration for a duration of less than 2 or 3 seconds, typically once or twice a week or more rarely once a day. It would clearly be illusory to use data on continuous vibration or repetitive impulse vibration over long periods of time as a criterion. However, it is clear that from the point of view of annoyance, structural vibration cannot be treated as a separate phenomenon from the simultaneous acoustic wave.

3. PROCEDURE FOR TESTS

In this study, overpressure measurements were made during blasting operations at four quarries in southern Ontario. Three of these are located on the Niagara Escarpment and the aggregate produced is predominantly limestone. The fourth is a much smaller quarry located within Metropolitan Toronto and the aggregate is shale.

During two of the blasts, simultaneous vibration measurements were taken by the quarries' blasting consultants. This enabled comparisons to be made between overpressure and vibration.

3.1 Blasting Procedure

In all of the quarries visited, multi-delay blasting is used in order to control noise and vibration as well as to obtain a suitable type of "break". Various detonating systems can be used, however, the two major types which are used here are briefly as follows (28).*

3.1.1 Blasting with Detonating Cord Trunk Line

The firing system used at Milton and Indusmin (Acton) quarries is a "toe-detonation" system employing a surface line (trunk line) of detonating (Primacord) cord, see Fig. 22.

The "anoline" down line is a low strength detonating cord which by itself will not fire the AN/FLO blasting agent (ammonium nitrate/fuel oil) but which will fire the blasting cap at the base of the hole. This in turn fires the blasting slurry and detonates the "primacord" up-line. The Primacord is a highly explosive cord (20, 350 ft/sec propagation velocity) which fires the 1 lb. primers and thus the AN/FLO blasting agent.

Twenty-five millisecond relays are placed in the main trunk line to achieve this delay between the firing of each hole. As a safety feature, each of the up-lines is attached to a secondary trunk line which runs parallel to the main line but contains 35 ms relays between holes. This then forms a backup system should a break occur in the main trunk line.

The use of a number 4 (100 ms) blasting cap (toe-det cap) in each of the holes is an additional safety feature which ensures that detonation of the cap has started in the 5th hole before the first hole explodes. In this way, cutting of the up or down lines by rock movement is only likely to occur after the caps have been initiated and then the explosive below the cut will still fire due

* Also verbal communication with L. Karp, Boyes Explosives

to the cap, whilst that above the cut will be fired by the backup system.

The firing sequence is initiated by an electric starter and blasting machine. The trunk lines are often burried in sand to prevent oil or water contamination and to some degree, reduce the sharp crack which it is known to produce.

3.1.2 Blasting Electrically

At Dufferin Quarry the firing is initiated at the tops of the holes as shown in Figure 23. Electric lines only are on the surface and these initiate electric delay caps which in turn fire Primacord "down lines" and primers. The delay caps are initiated simultaneously but have progressively longer delay times to achieve the required delays between holes. The delay caps may be connected either in series or parallel.

At Toronto Brick Quarry, several delays are used within each hole so as to minimize noise and vibration in the adjacent residential area.

The types of explosive used in quarry operations vary considerably according to the type of "break" required, the geological formation and the climatic conditions. In any single blast, several different types are usually employed. In this study, the weight of explosive has been used as a major parameter and no attempt has been made to compare the results of different explosive.

3.2 Monitoring Systems

Two basic systems were used for monitoring the blasts, both incorporating a Brüel and Kjaer 4147 sonic boom microphone and 2631 microphone carrier system. This system will detect pressure variations at frequencies as low as 0.001 Hz. However a lower limiting frequency of 1 Hz was used during these experiments because of the extreme sensitivity to even light winds at lower frequencies.

The first system (A) used, is shown in Figure 24 consisting of the sonic boom microphone - carrier system, an electret "trigger" microphone, preamplifier and Tektronix storage oscilloscope. The procedure used was to set the trigger microphone several feet ahead of the sonic boom microphone and connect it to the trigger input of the oscilloscope which was set in single sweep mode with the storage facility on.

When a pressure pulse reached the trigger microphone, this would start the single sweep of the oscilloscope and the signal received via the sonic boom microphone was stored on the screen. The distance D between the microphones was adjusted according to the time base used on the oscilloscope to obtain a trace centered on the screen. If the signal from the sonic boom microphone had been used to trigger the oscilloscope, then because of the slight delay inherent in the oscilloscope, the beginning of the trace would be lost. Therefore the oscilloscope had to be triggered the equivalent of about one division (secs) before the sonic boom microphone received the signal. For example, with a time base of 50 ms/div, the microphones would be set 50 feet apart so that with the pressure wave travelling at about 1100 ft/sec the delay would be 50/1100 sec, ie. approximately 50 ms or one division.

The preamplifier was used as an additional trigger level adjustment, set low enough that the blast would trigger the system and high enough that the spurious low level sounds would not. Once the signature was obtained on the oscilloscope screen, it was photographed with polaroid film.

This system has been used for sonic boom measurements but has some major disadvantages for blast recording. The first problem was encountered when attempting to monitor a blast, where a long primacord trunk line triggered the oscilloscope prematurely and the blast occured after the single sweep had passed.

The second disadvantage arose because the overpressure level produced by blasting is far more variable than for sonic booms. This means that the gain setting used on the oscilloscope can easily be set too low whereby a very small trace will result, or it can be set too high and result in the signature going off scale. A lesser, though still significant problem was that polaroid film develops unpredictably, producing poor results at the low temperatures prevailing during the initial measurements. In spite of the above, some useful data was obtained with this system.

The second system (B), see Figure 25, employed a Hewlett Packard four channel FM tape recorder with the sonic boom microphone-carrier system providing the input to one channel and two sound level meters providing the input to two other channels. The attenuator settings on the meters were set so as to cover pressure ranges above and below that of the carrier system should an unexpected level occur. The meters used were a Brüel and Kjaer 2209 with a 4133, $\frac{1}{2}$ inch microphone and a Brüel and Kjaer 2204 with a 4145, 1 inch microphone. The 2209 - 4133 system has frequency response:

10 - 8 KHz $\pm$ 0.5 dB
6 - 20 KHz $\pm$ 1.0 dB
4 - 40 KHz $\pm$ 2.0 dB

and the 2204 - 4145 system:

6 - 4 KHz $\pm$ 0.5 dB
4 - 12 KHz $\pm$ 1.0 dB
3 - 18 KHz + 1.0 dB
- 1.5 dB

This means that in the few measurements where sound level meter results only were obtained, (or were the only ones readable) some error was involved due to the low frequency "roll off".

3.3 Analysis System

With system A the only analysis possible was calculation of overpressure and duration from the photograph and sometimes an estimate of the principle frequency component.

With the second system B, the taped record allowed for pressure versus time signatures to be obtained on the oscilloscope in the laboratory (Figure 26). In this way, various time scales could be used to examine parts of the trace in detail or the whole duration. Also the gain on the oscilloscope could be varied to obtain a clear trace. In addition, a spectral analysis of each of the recorded blasts was carried out using the "Transient Capture" facility of a Spectral Dynamics SD 301D Real Time Analyser. These spectra were displayed on the oscilloscope and photographed.

Although the spectrum produced by a real time analyser for transients is not a true Fourier analysis, it does give a good approximation to the relative amplitude of the frequency components of the transient.

4. RESULTS

4.1 Simultaneous Vibration and Overpressure Measurement

Two simultaneous vibration and overpressure measurements were taken at Indusmin. The first location was 2000 feet in front of the face and the second, 700 feet behind the face, see Figure 27. The charge per delay was similar in the two cases, 2008 lbs average in the first and 1768 the average in the second with a maximum in the second case of 1950 lbs.

Figure 28 shows the pressure vs time trace obtained using system A described above. As can be seen, the trace exceeded the range expected on the first peak but was nevertheless greater than 4 psf. The unexpectedly high overpressure was judged to be due to the strong wind, about 30 mph blowing from the direction of the face to the microphone. The seismic recording (by VME Associates) showed a peak particle velocity of 0.04 ins/sec vertically.

Figures 29a to 29d show the rather better results obtained at the second location. Figure 29a shows the whole duration of the pressure disturbance and Figure 29b the relative amplitude level, dB vs log frequency. The peak of the trace is shown in Figure 29c to an expanded time scale and the lower end of the spectrum, 1 Hz - 100 Hz, is shown in Figure 29d. The peak overpressure in this case was 2.7 psf and the peak particle velocity 1.6 ins/sec radially.

Two blasts separated by about three minutes were monitored at Milton Quarry (Figure 30). The first blast (Figures 31a, b) consisted of fifteen holes and the second, eight holes (Figures 32a, b). The peak overpressure for these two blasts at 1100 ft in front of the face were 2 psf and 4 psf respectively. The quarry monitored vibration at 1500 ft in front of the face and obtained 0.16 and 0.18 in/sec peak particle velocity respectively.

It is clear from the literature cited on sonic booms that in all of these cases, some minor damage could have been incurred by a structure exposed to such overpressures. The ground vibration level however, measured in front of the face was quite insignificant in all three cases.

For the measurement behind the face, i.e. where there was no large discontinuity in the ground between the charge and monitoring location, the ground vibration was quite considerable although short of the threshold of damage. The overpressure and ground vibration would have both contributed to significant structural excitation in this case.

4.2 Error Due To Frequency Response Fall-Off Of Instrumentation

Figure 33 shows the arrangement of, and Figure 34a - 34d the results of another blast at Indusmin. These results indicate the error involved in using instrumentation without the sonic boom system low frequency characteristics. Figures 34a, b show the pressure vs time signature and spectrum obtained with the sonic boom system and Figures 34c , d show the same blast as monitored with the Brüel and Kjaer 2209 sound level meter and 4133 $\frac{1}{2}$ inch microphone.

The pressure vs time traces are quite different. The sonic boom system gives the peak pressure perturbation as positive, equal to 2.2 psf. The meter measurement gives the peak as negative and 1.6 psf. In the latter case, the first positive peak is 1.3 psf. The error involved in using the meter would have been 3dB (132 dB rather than 135 dB).

Examination of the spectra of the two measurements, indicates clearly the reason for the error: the presence of a significant contribution at 2 - 3 Hz absent from the meter recording.

A similar comparison can be made with the results of a blast monitored at Dufferin (Figures 35, 36a - 36d). In this case the levels do not appear to differ much, if at all, although it is difficult to determine the exact peak of the meter recording.

4.3 Toronto Brick

Toronto Brick's quarry is unusual in that because of the sensitivity of the area, very small charges are used. Two measurements made using sound level meter inputs only, gave the results shown in Figures 38 and 40 at locations 500 and 150 feet in front of and behind the face respectively.

4.4 Comparison of Blast and Sonic Boom

4.4.1 Overpressure

The peak overpressure measured during the eleven tests are summarized in Table 14. This includes three measurements not described above, one at Milton Quarry where the peak overpressure was obtained with a direct reading meter and two at Dufferin Quarry where the results were readable, although not of high quality. They have also been plotted in Figure 41 vs scaled distance $\frac{D}{W^{1/3}}$, and the scaled depth $\frac{d}{W^{1/3}}$ is indicated. The depth d was taken to be the stemming height. Figure 41 also includes three of the BRL curves for scaled depths of $\frac{1}{2}$, 1 and $1\frac{1}{2}$.

Comparing the overpressures obtained with those in Tables 2 through 7 and Table 12, it is clear that overpressures capable of causing minor damage, ie. exceeding 2 psf are quite possible within several thousand feet of a quarry blasting operation, particularly if unfavourable climatic conditions prevail, such as temperature inversions or strong winds in the direction of residences.

The superposition of the measured points on the BRL curves in Figure 41 indicates that based on the stemming height as the effective depth of the charge, the levels obtained are, in general, higher by 10 dB or more in the case of measurements made in front of the face. The four measurements made behind the face are in closer agreement with the BRL curves.

4.4.2 Spectra

The characteristic frequency spectrum of an ideal sonic boom N wave is as shown in Figure 42, having a peak amplitude in the infrasonic range at about 10 Hz or lower and decreasing at 6 dB/octave so that contributions above 500 Hz are at least 40 dB below the peak amplitude level. Measured sonic boom spectra are rather more irregular due to the effects of turbulence in the lower atmosphere. See Figure 43.

All the blast spectra measured except the blast at Indusmin shown in Figure 34b had the maximum component in the low infrasonic range. Figure 34b shows a peak component of 25 Hz, slightly higher than the

amplitude peak at 9 Hz and a very steep fall-off just below 50 Hz.

Figure 36b, the spectrum of a blast at Dufferin is close to the characteristic sonic boom spectrum, and the other spectra measured tend to show secondary peaks in the low sonic range. These secondary peaks may be due to the exploding detonating cord. In all cases, contributions from frequencies above 500 Hz are 40 dB or more below the amplitude of the peak frequency component.

4.4.3 Duration

The duration of the signature of a sonic boom is a function of the size of the aircraft and the speed along the ground track, as these determine the time elapsed between the front and rear shocks passing a stationary observer on the ground. The durations therefore vary from t = 0.04 secs for a fighter aircraft to t = 0.4 secs for a supersonic transport.

The duration of the blast signature is a function of the number and length of delays. However most of the measured blasts show durations considerably in excess of the sum of the delay times. The range of durations measured are 0.14 - 2.7 secs (Table 14), ie. generally several times longer than the sonic boom signature.

5. Discussion

The experiments carried out have shown that the acoustic wave associated with a quarry blast bears some close resemblances to the pressure signature of a sonic boom:

The overpressures experienced up to several thousand feet from a blast can be of the same order as those produced by a sonic boom.

The spectra are very similar with a maximum amplitude in the low infrasonic range and little contribution above 500 Hz. The blast tends to have a relatively greater contribution in the low sonic range which would make it subjectively louder than the boom for the same peak overpressure.

The duration of a blast is up to six times longer than that of a sonic boom, 2.7 sec being the longest measured in this series, which again would tend to be more annoying particularly indoors where reverberation would extend the duration even further. Sonic boom studies suggest that for durations up to half a second, variations in duration have little effect on subjective loudness. However comparisons with jet noise of about 12 sec duration suggest that at this length there would be a significant effect due to duration. The relatively long duration of the blast with principal frequency components in the range of structural modes of vibration makes the excitation of structures more probable.

It can be concluded that from the points of view of damage and annoyance, the criteria derived from sonic boom studies may be reasonably applied to blast produced acoustic waves, although the effects of the latter may be a little more severe for the same overpressure.

In the St. Louis study (4) the frequency of exposure, 40 booms over a four month period, was the closest of the studies cited to the typical frequency of quarry blasts. Therefore we may say that probable public reaction will occur at overpressures of 1.0 - 1.5 psf.

Minor damage such as cracked windows or plaster can occur at overpressures as low as 2 psf.

Where there is a large physical discontinuity between the blast and the receiver of the air and ground wave, such as the quarry face then

ground vibration is likely to be insignificant compared with the air wave, both for structural excitation and the associated human annoyance. Where there is no major discontinuity, the effects of the two waves will be additive.

In order to minimize adverse public reaction the air blast overpressure should not be greater than 1 psf and the ground vibration not greater than 0.4 in/sec peak particle velocity at the nearest residence. To achieve these objectives some rule or guide is clearly necessary.

Predictions of overpressure based on scaled distance and scaled stemming depth according to the Ballistics Research Labs (2) curves, give levels lower by 7 - 15 dB than in fact occured for locations in front of the quarry face. This is probably because the "break" is through the face and consequently the effective depth of the charge may be quite small on the side of the face.

More data points are needed to establish adequately a relationship between overpressure, scaled distance and scaled depth. It would be preferable for a quarry to calibrate the particular operation in a similar way to the U.S.B.M.'s method for vibration. This would give two minimum scaled distances, one for vibration and one for overpressure. For a given distance, the charge size would be calculated both ways and the lower value applied.

Refraction due to temperature inversion and wind gradients, and reflection due to low cloud can have a significant effect on the propagation of a blast wave. Quarry operators try, in general to avoid blasting during low cloud and inversion conditions, however once the charge has been loaded, there is a limit due to safety considerations that firing may be delayed, if the weather closes in.

Refraction can result in larger overpressures far away from the blast and relatively low overpressures at shorter distances. Such effects can result in increases in pressure level of the order of 10 dB.

The advisability of monitoring airblast as well as ground vibration has been demonstrated. The system used in this study, while

reasonably compact is rather expensive and not as portable as most consultants would prefer. Little error would be involved if a precision sound level meter with a 'peak hold' facility were used. The meter should be used with 'linear', ie. flat response and the meter-microphone system should have a flat response to 3 Hz $\pm$ 1 - 2 dB. Such a meter could in fact be fitted with a sonic boom microphone or an existing microphone modified by partially sealing the pressure equalization hole so that the lower limiting frequency becomes determined by the meter which may be about 2.5 Hz.

If such measurements were made on a routine basis, along with vibration velocity measurements, sufficient data would rapidly be available to predict peak overpressure from quarry blasting with a reasonable degree of accuracy.

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FIGURES

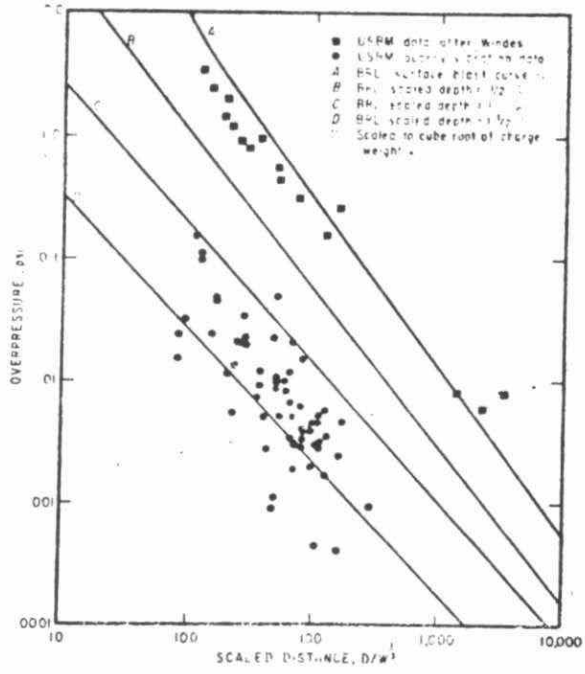


FIG 1 COMBINED DATA PLOT,
OVERPRESSURE VS. SCALED DISTANCE (2)

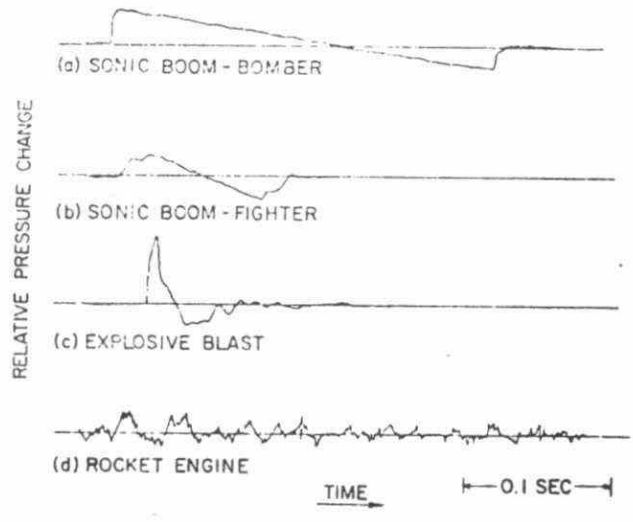


FIG 2 TYPES OF PRESSURE LOADING FOR WHICH BUILDING
RESPONSE MEASUREMENTS WERE OBTAINED (10)

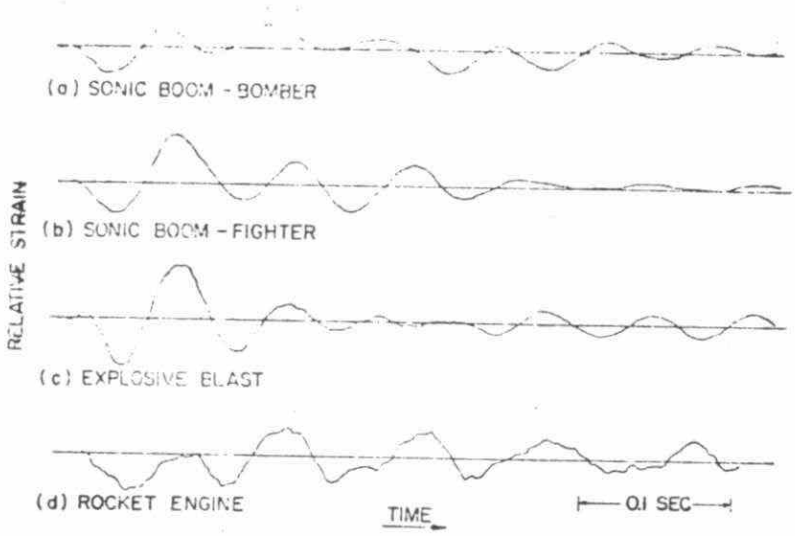


FIG 3 TRACING OF TRANSIENT STRAIN RESPONSES FOR A VERTICAL STUD OF THE TEST BUILDING TO THE PRESSURE LOAD OF FIG 2 (10)

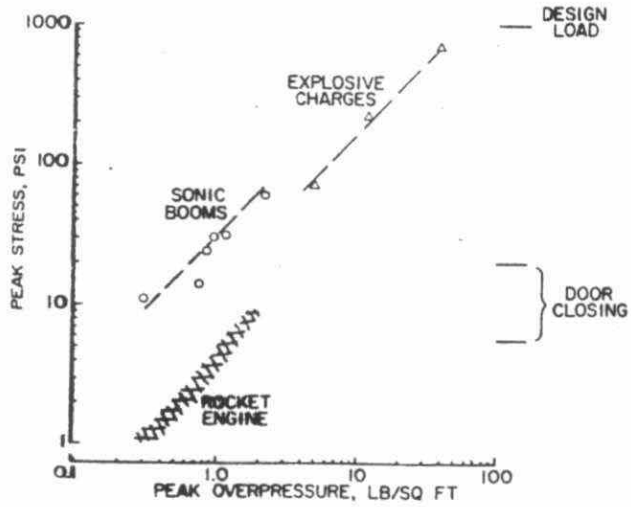


FIG 4 PEAK OF VERTICAL STUD STRESSES AS A FUNCTION OF PEAK OVERPRESSURE FOR VARIOUS TYPES OF EXITATION (10)

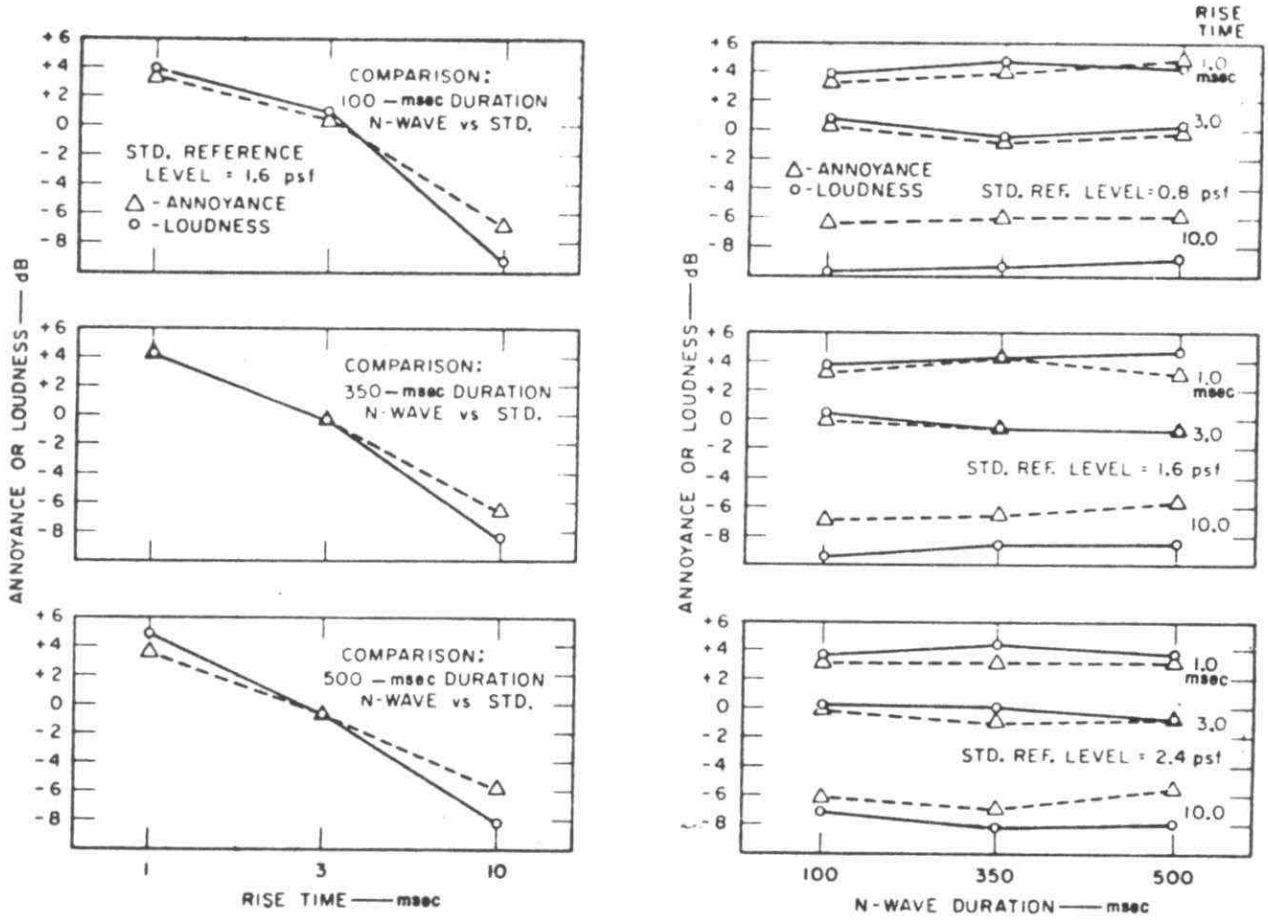


FIG 5 RELATIVE LOUDNESS AND ANNOYANCE VS. RISE-TIME OF SONIC BOOMS. LABORATORY FREE-FIELD JUDGEMENTS (14)

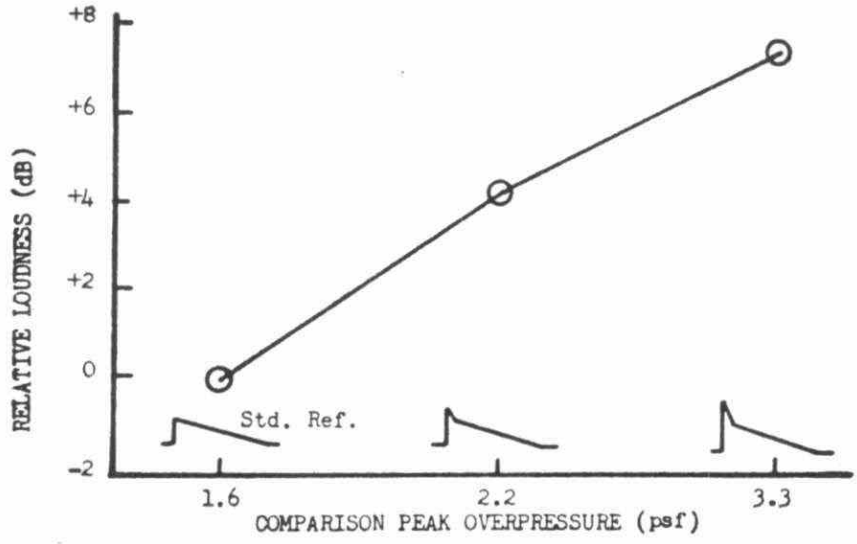


FIG 6 EFFECT OF A 'PEAKY' SIGNATURE (14)

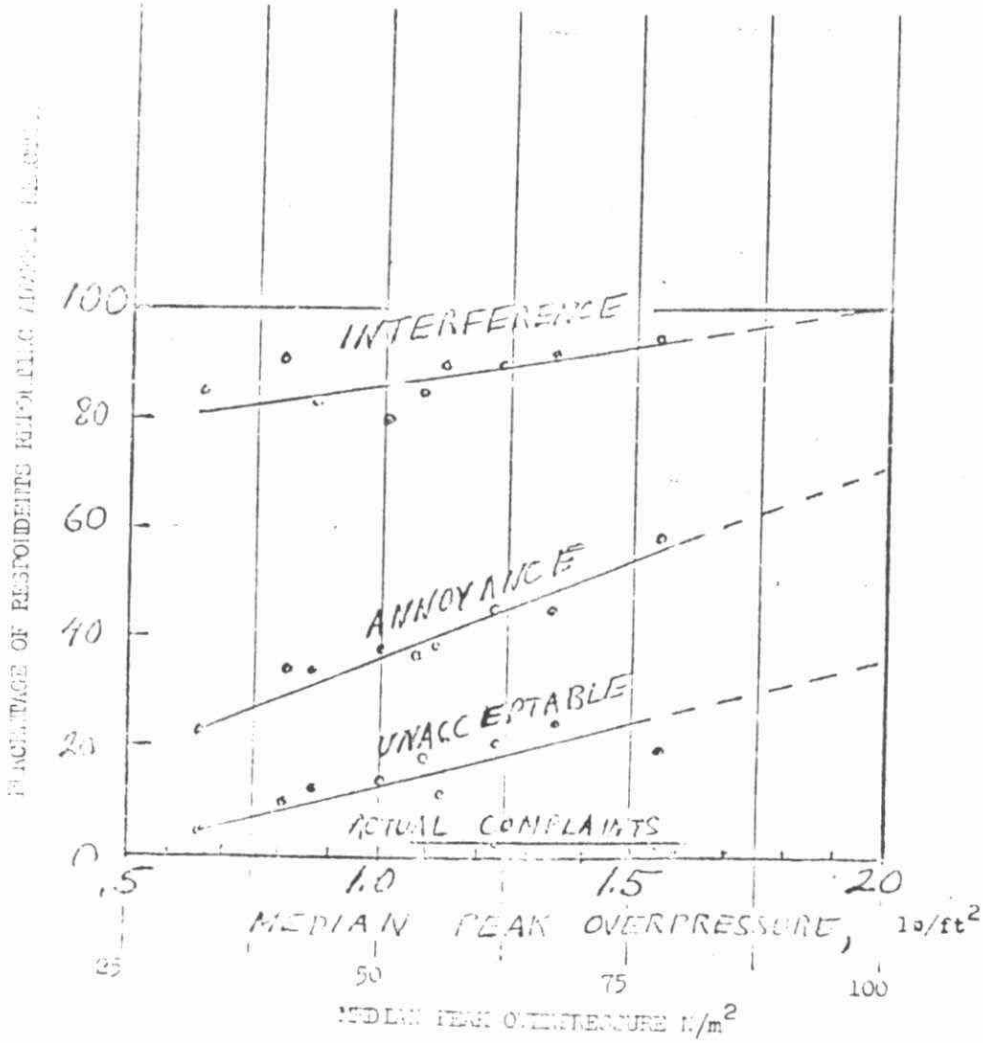


FIG 7 PER CENT REPORTING ADVERSE REACTIONS TO SONIC BOOM (7)

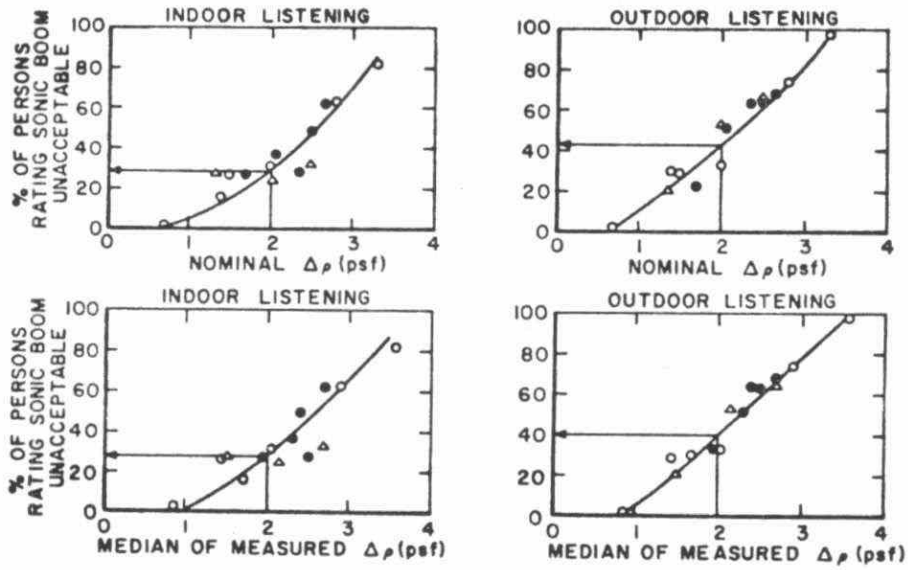


FIG 8 PER CENTAGE OF PEOPLE RATING SONIC BOOM UNACCEPTABLE RELATIVE TO NOMINAL PEAK OVERPRESSURE. RELATIVE ACCEPTABILITY OF INDOOR VS. OUTDOOR LISTENING TO THE SAME BOOM (14)

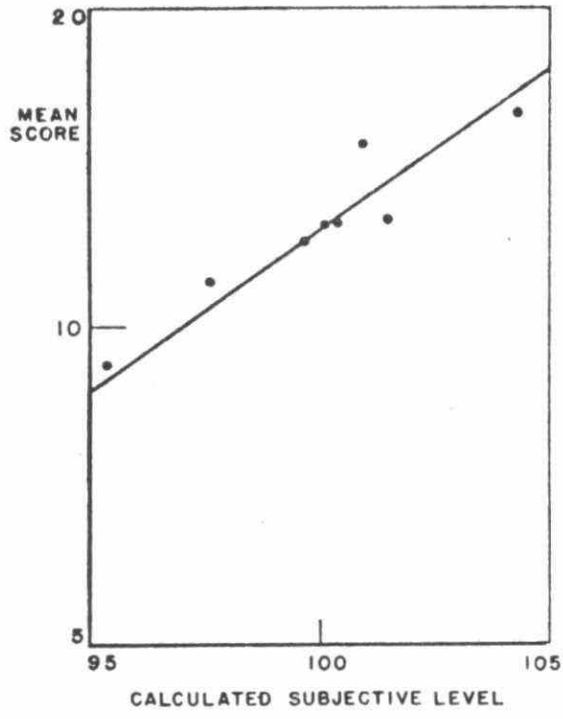


FIG 9 JURY JUDGEMENTS OF SONIC BANGS PLOTTED AGAINST CALCULATED SUBJECTIVE LEVEL (16)

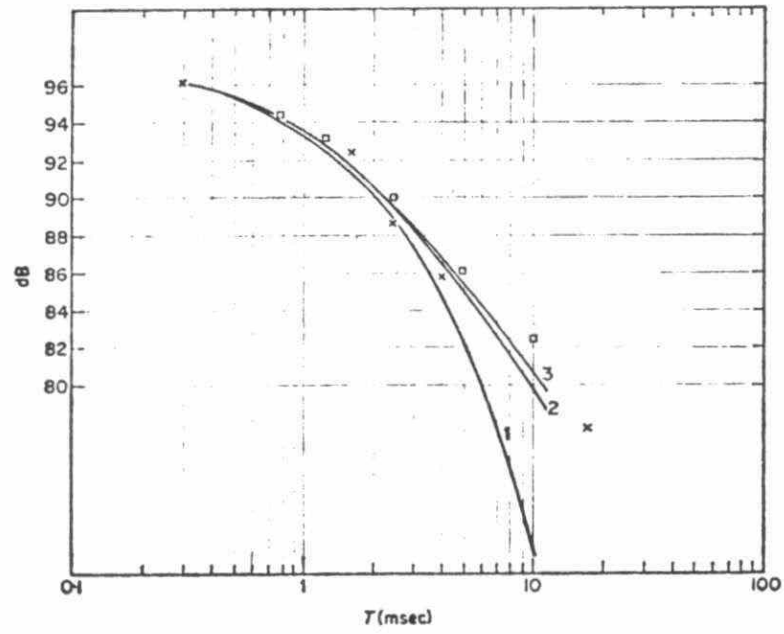


FIG 10 LOUDNESS VS RISE-TIME WITH CONSTANT MAXIMUM PRESSURE. EXPERIMENTAL (17)

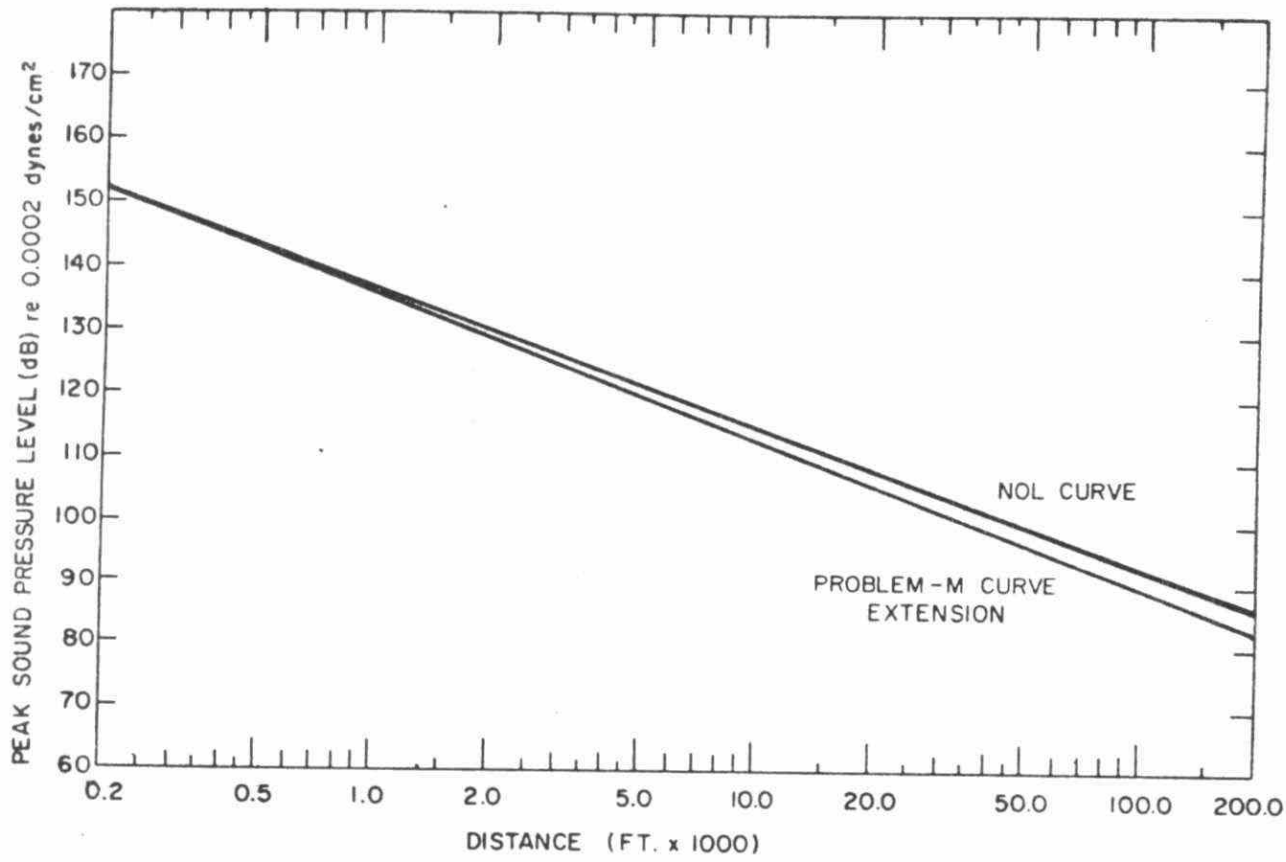


FIG 11 NAVAL ORDNANCE LABORATORY - BASE CURVE (18)

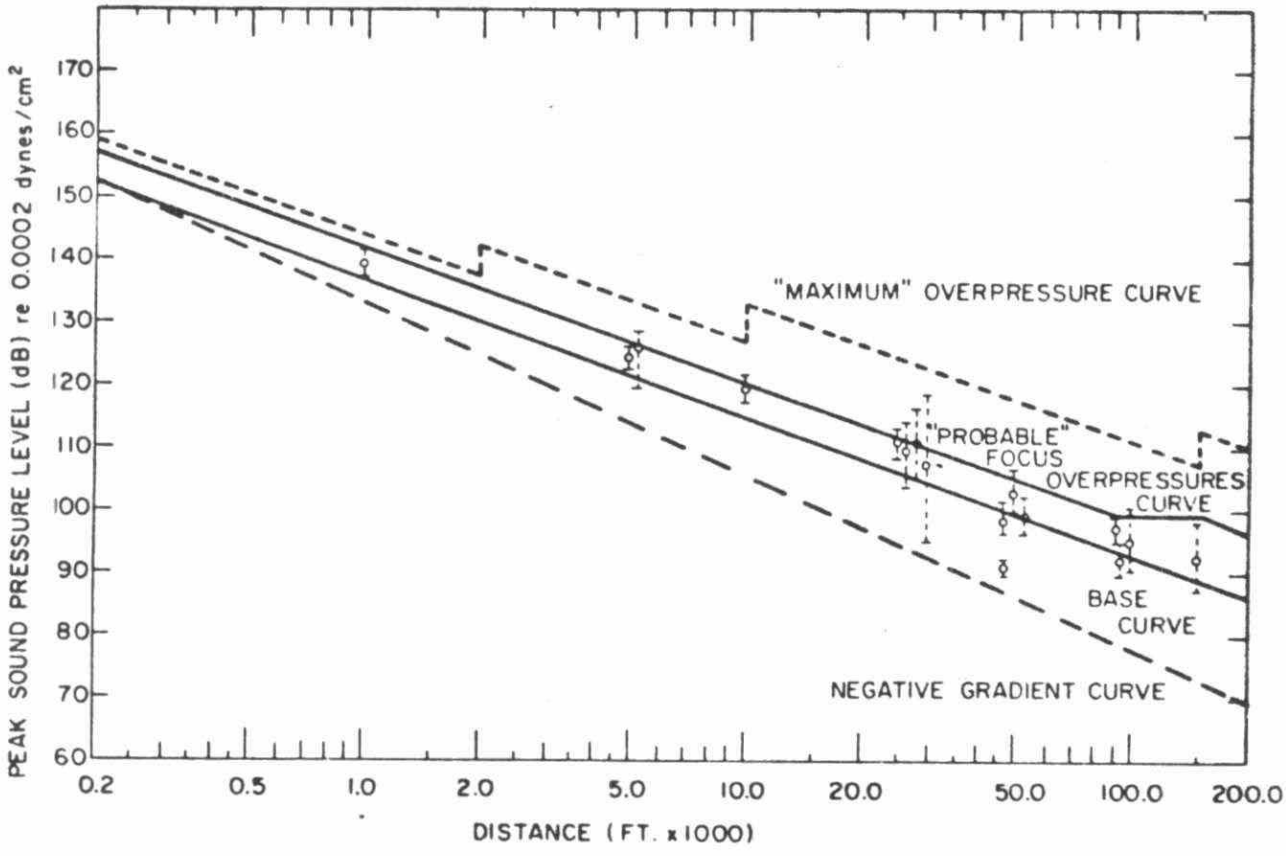


FIG 12 OVERPRESSURE PREDICTION FOR ONE POUND OF TNT (18)

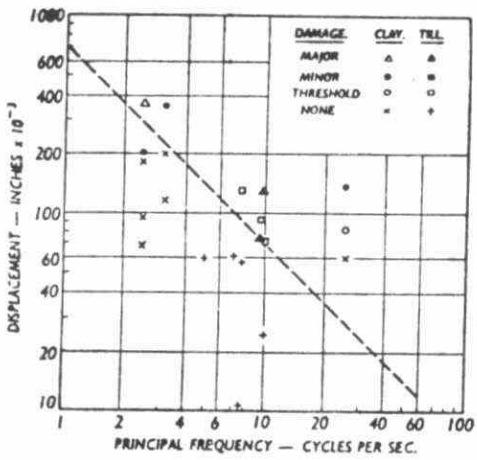


FIG 13 LONGITUDINAL DISPLACEMENT VS. FREQUENCY AND DAMAGE (3)

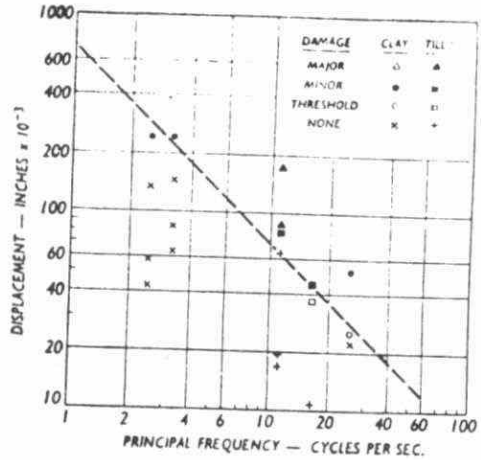


FIG 14 VERTICAL DISPLACEMENT VS. FREQUENCY AND DAMAGE (3)

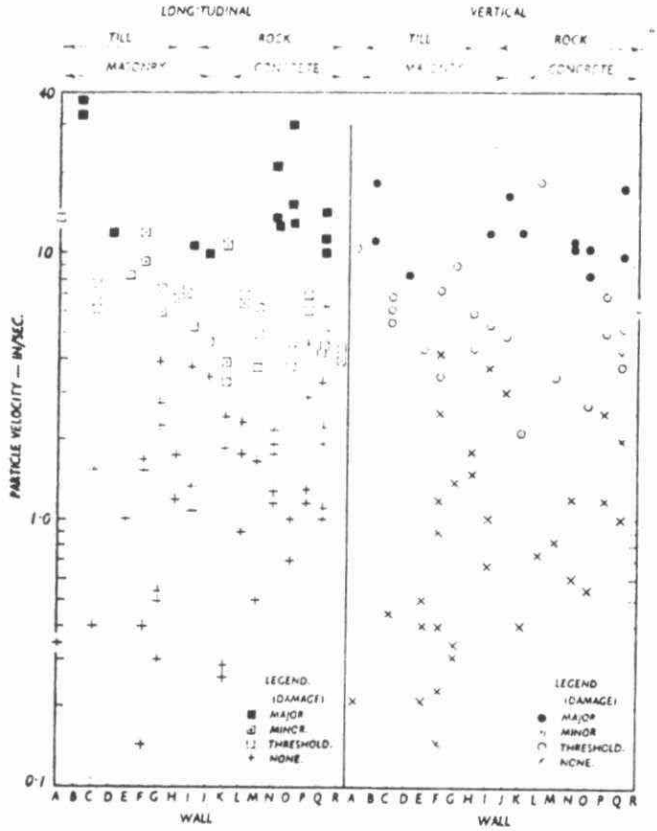


FIG 15 PARTICLE VELOCITY VS. DAMAGE (23)

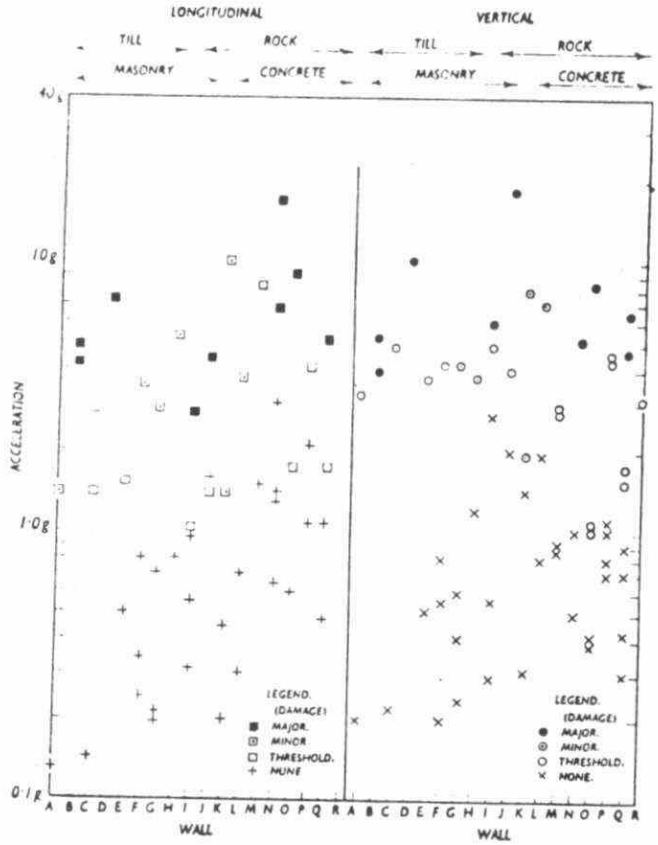


FIG 16 PARTICLE ACCELERATION VS. DAMAGE (23)

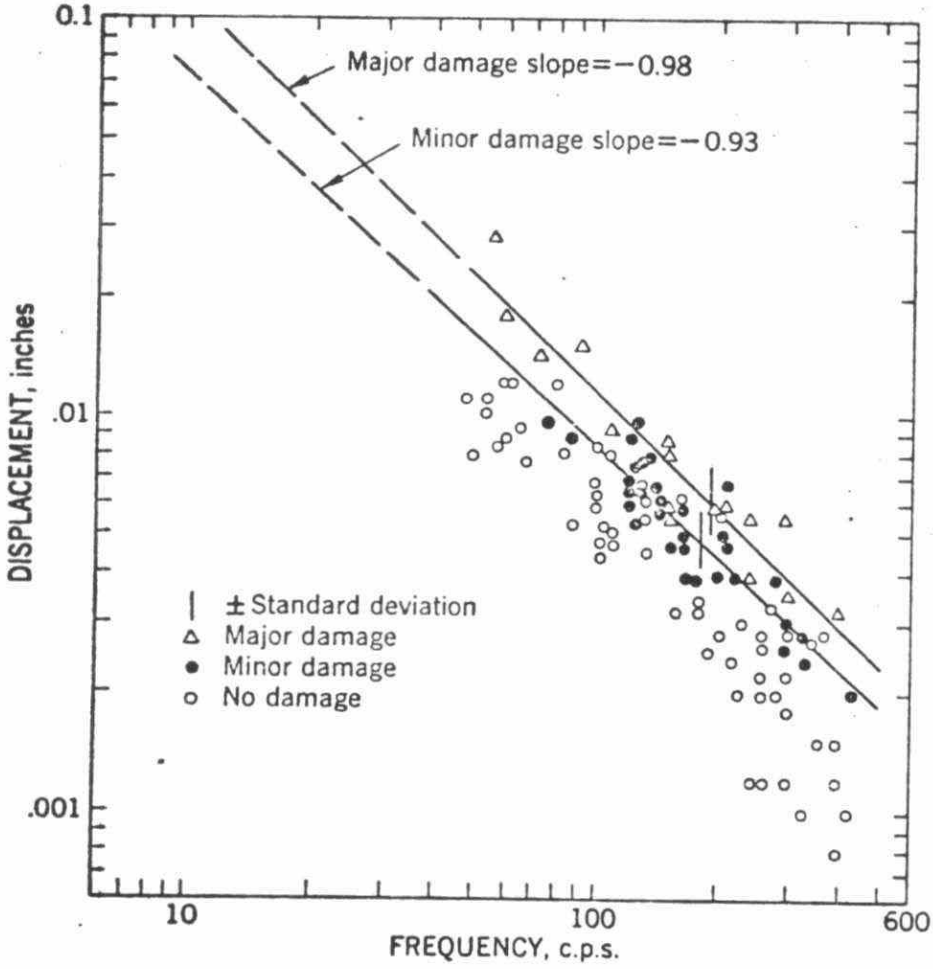


FIG 17 DISPLACEMENT VS. FREQUENCY FOR OBSERVED DAMAGE (22)

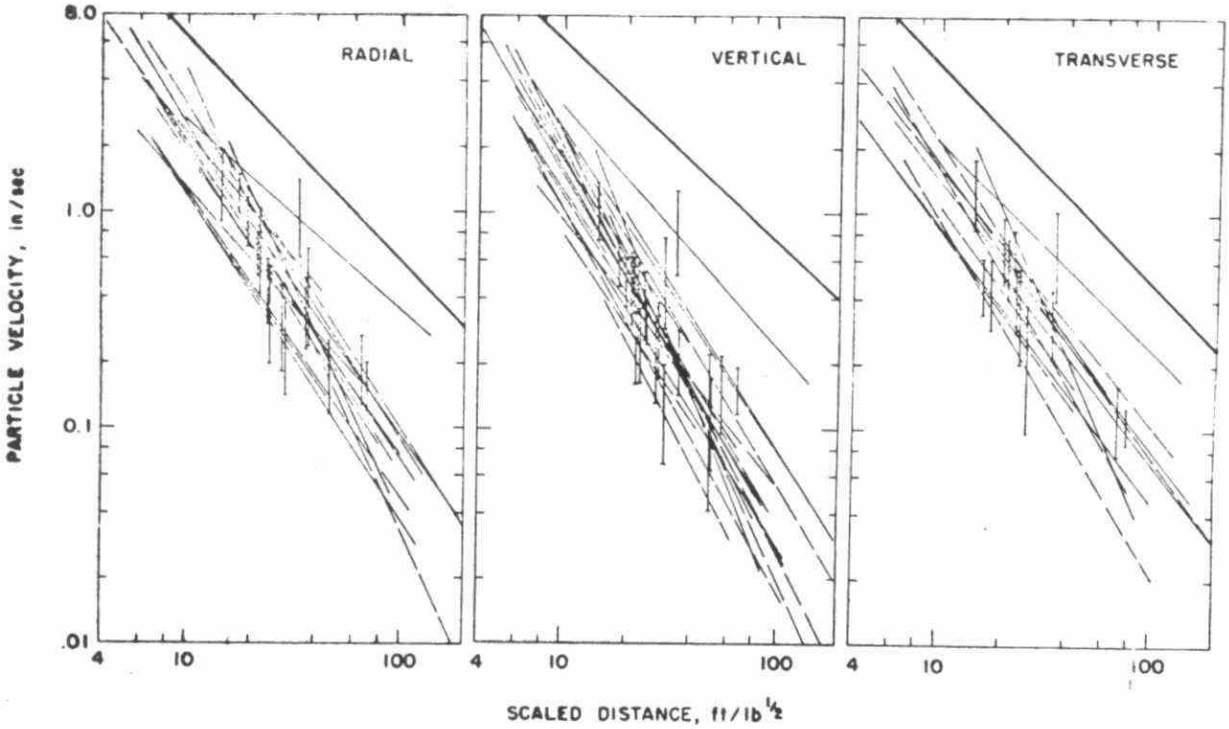


FIG 18 VELOCITY DATA VS. SCALED DISTANCE, FROM U.S. BUREAU OF MINES MEASUREMENTS (2)

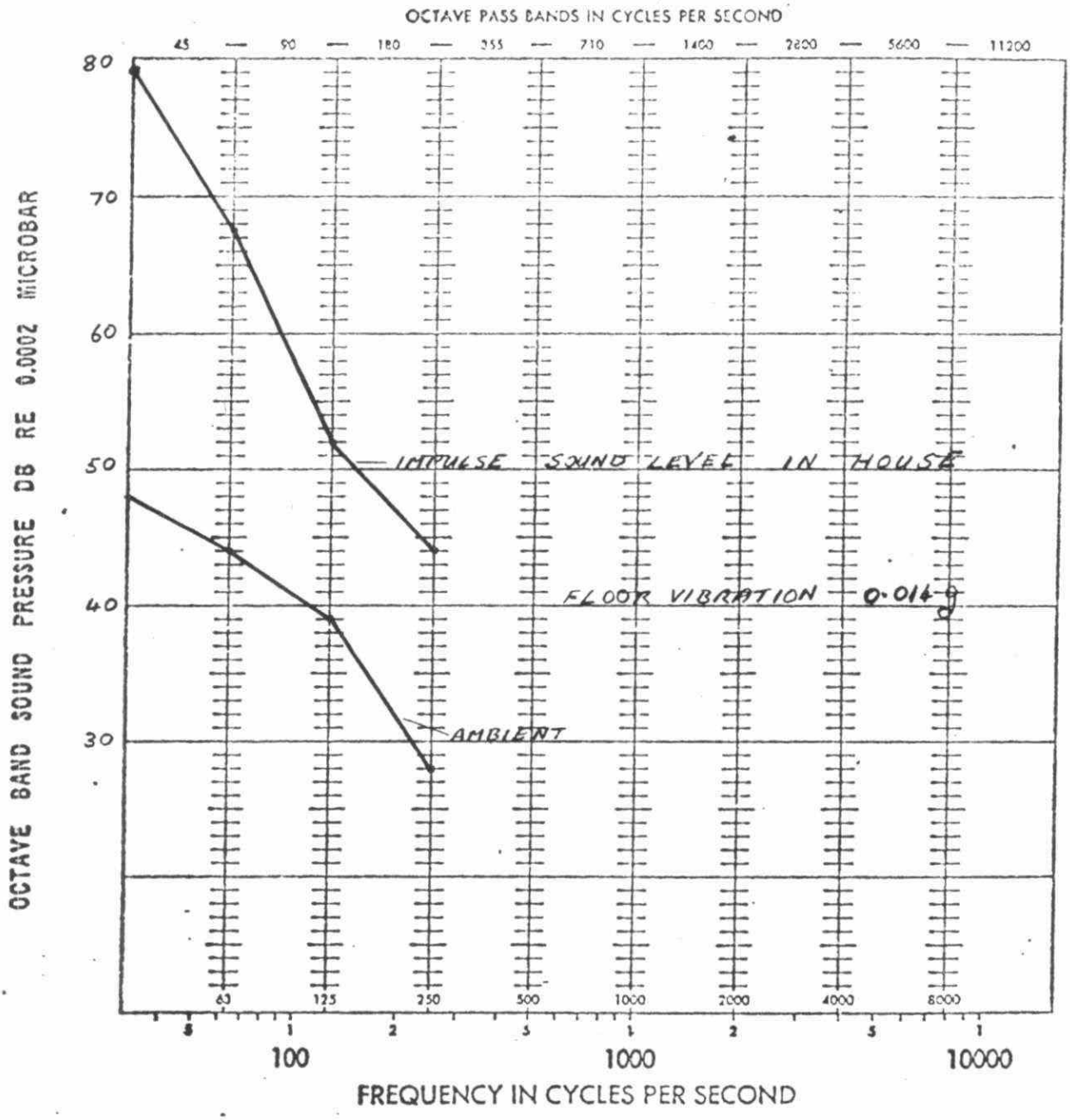


FIG 19 SOUND LEVEL IN RESIDENCE DUE TO GROUND-BORNE TRANSMISSION FROM 40 TON PRESS IN ADJACENT BUILDING (26)

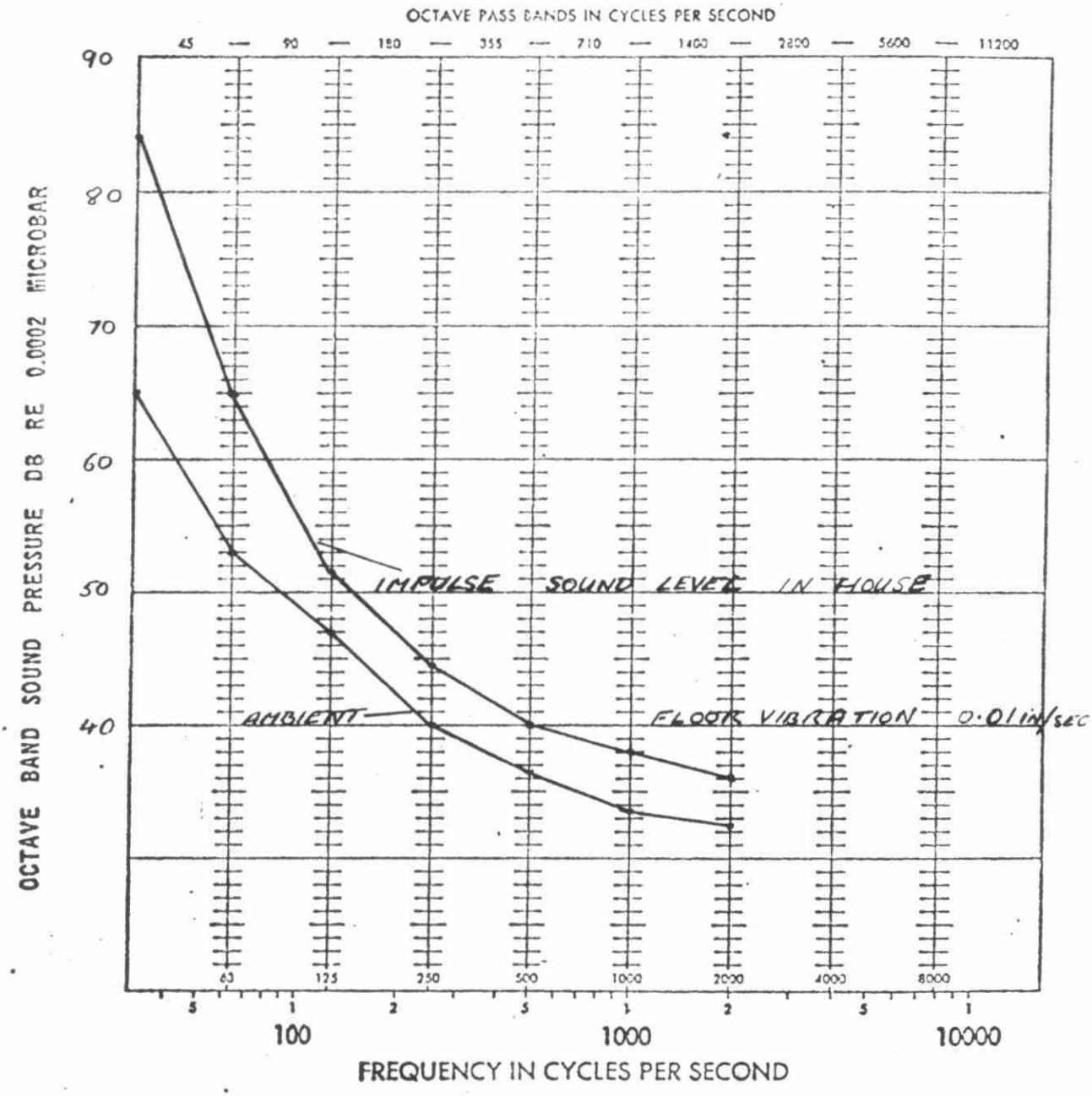


FIG 20 SOUND LEVEL IN RESIDENCE DUE TO GROUND-BORNE TRANSMISSION FROM IMPACT MACHINERY IN ADJACENT FOUNDRY (26)

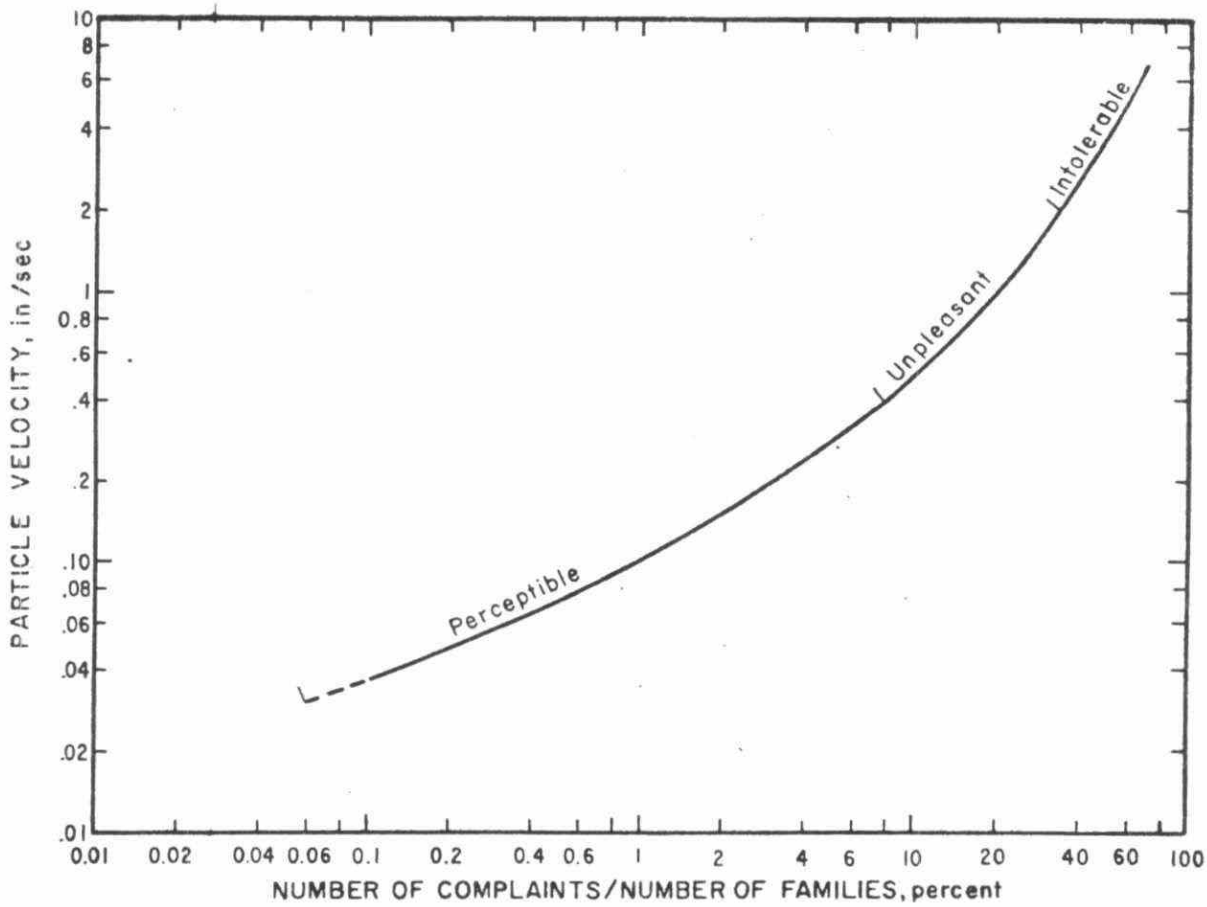
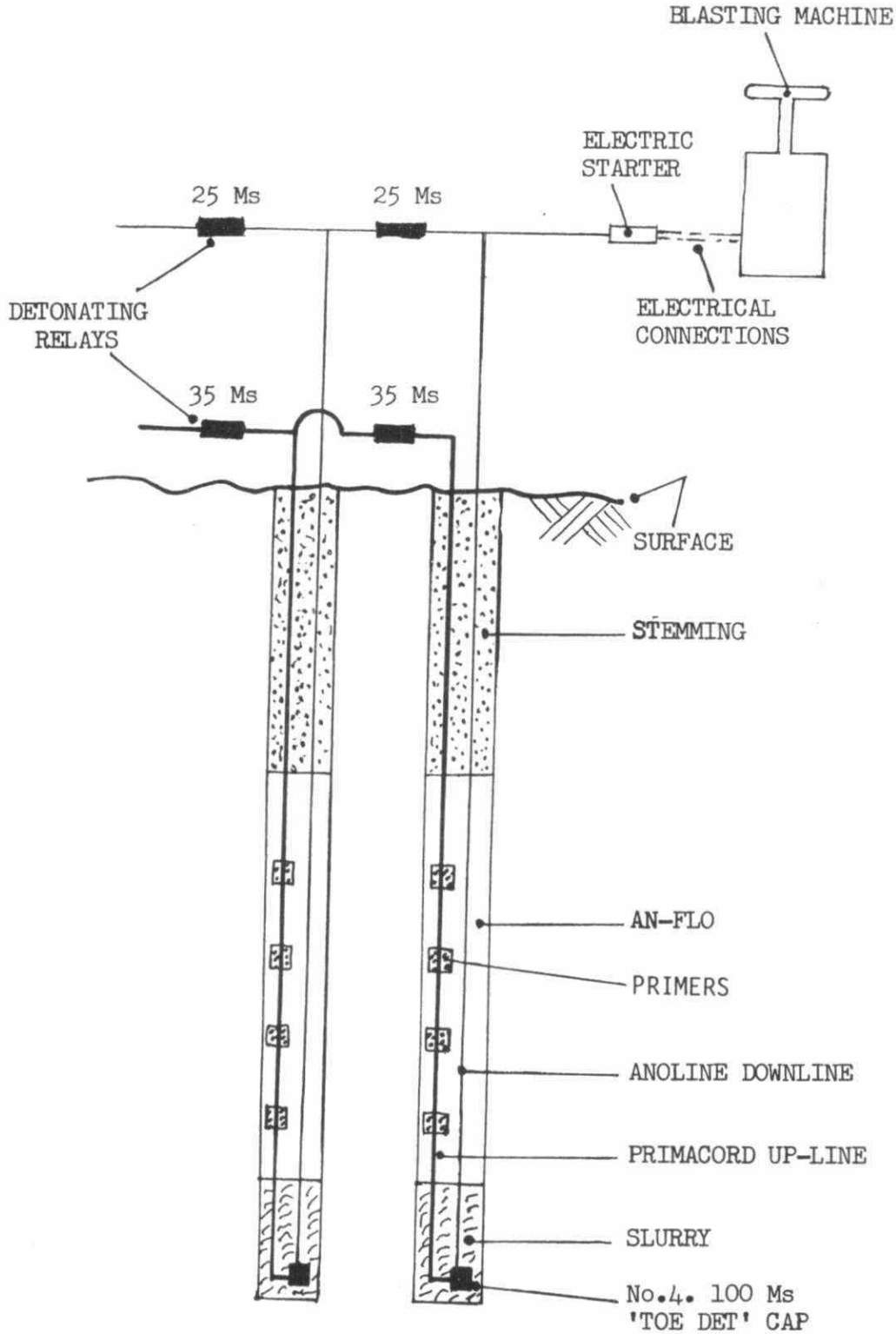
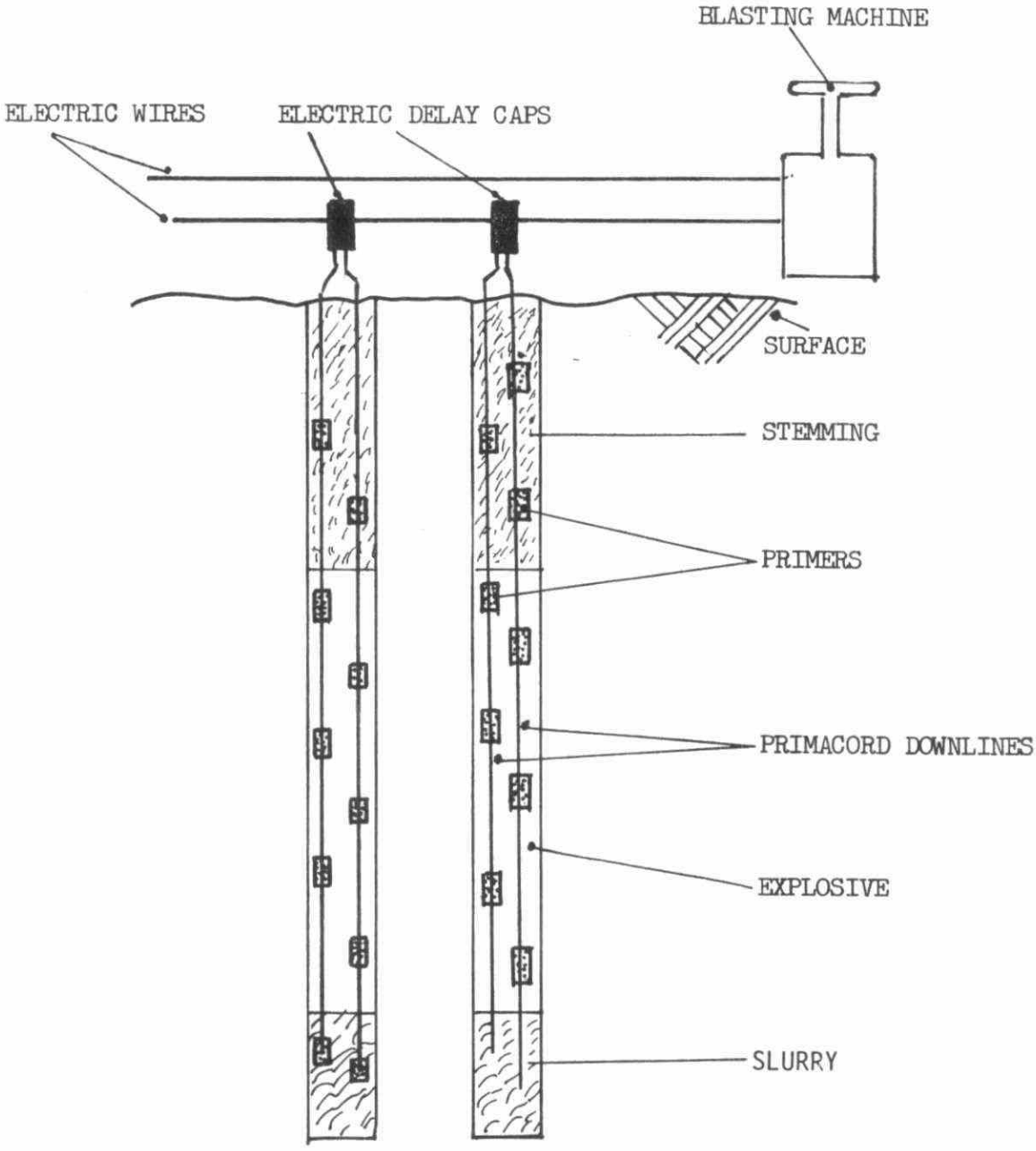


FIG 21 COMPLAINT HISTORY, SALMON NUCLEAR EVENT
WITH SUPERPOSED SUBJECTIVE RESPONSE (2)



SECTION THROUGH HOLES

FIG.22 BLASTING WITH DETONATING CORD (SCHEMATIC)



SECTION THROUGH HOLES (SCHEMATIC)

FIG. 23. BLASTING ELECTRICALLY

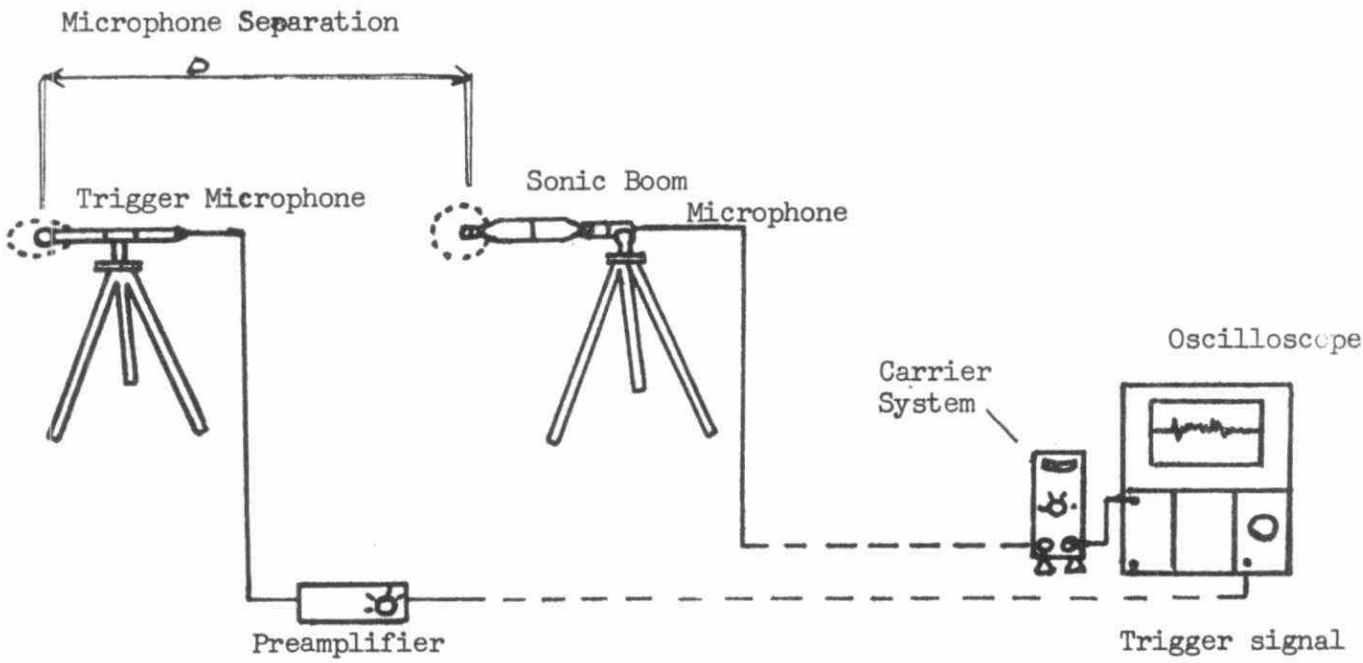


FIG 24 MONITORING SYSTEM "A"

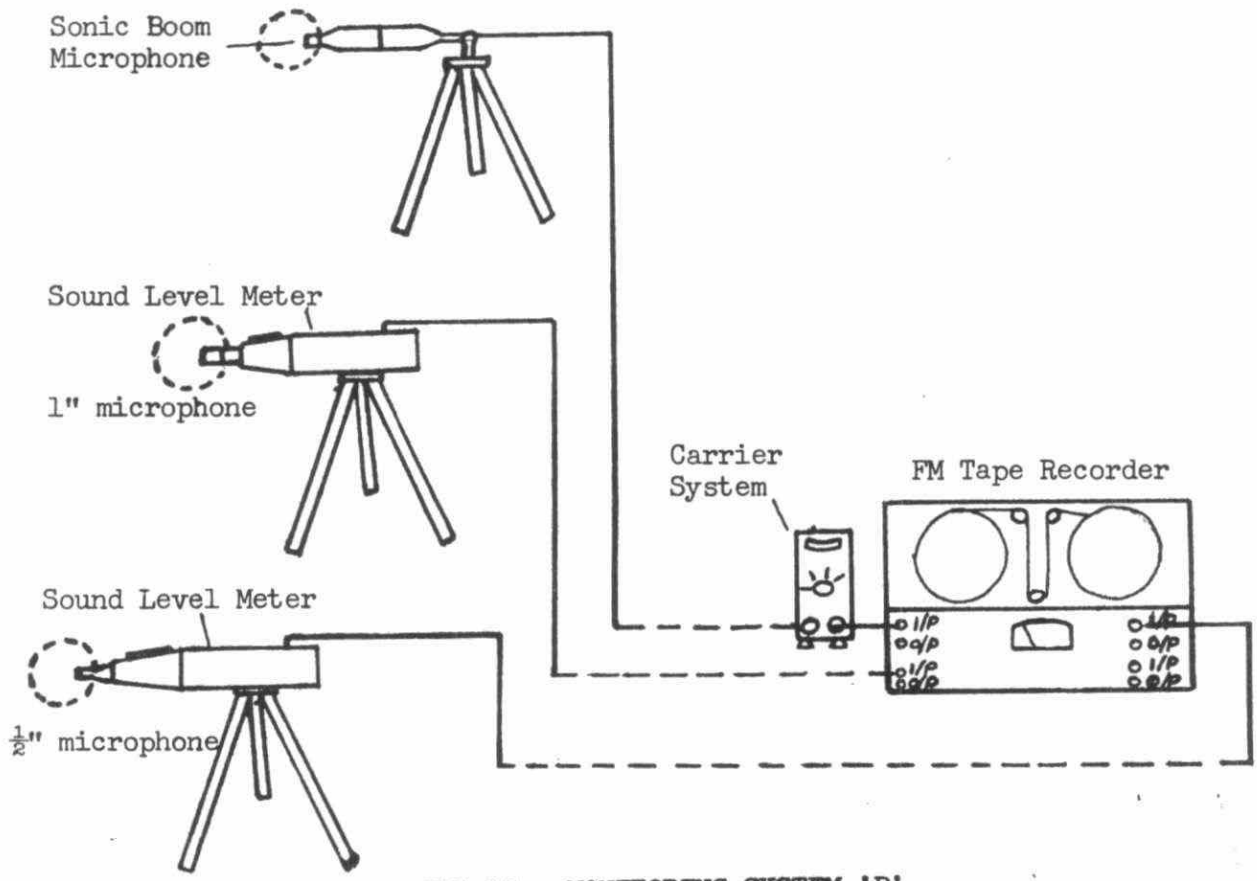


FIG 25 MONITORING SYSTEM 'B'

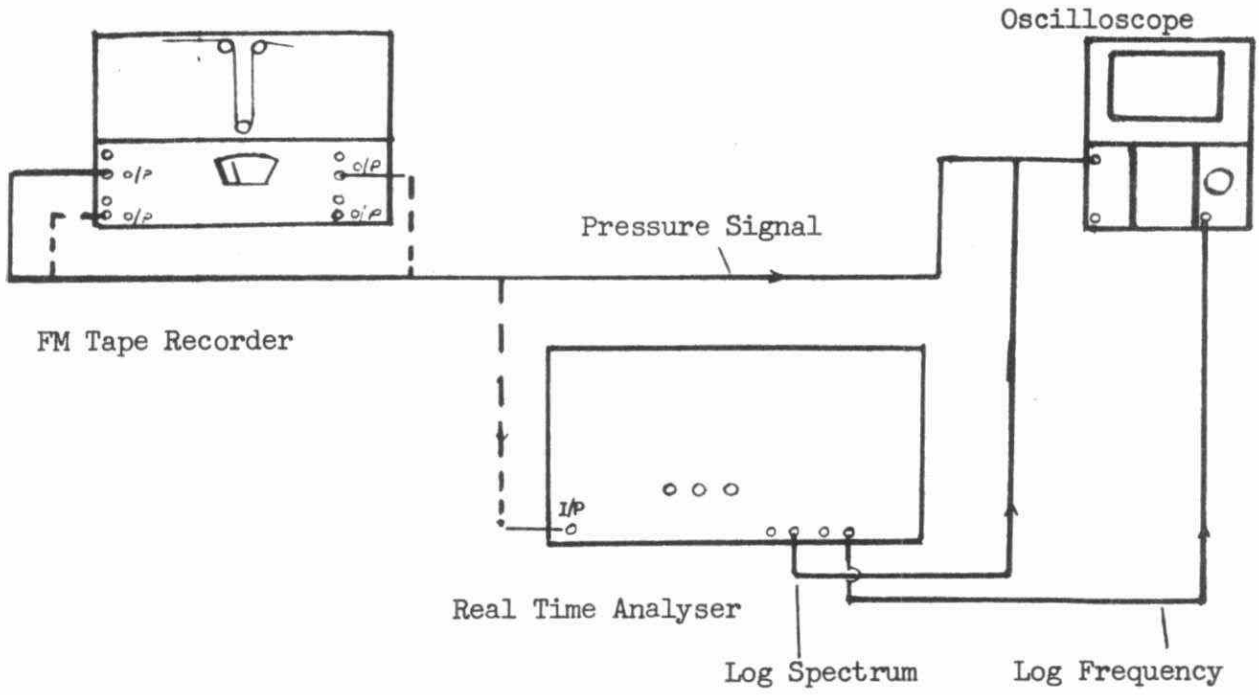
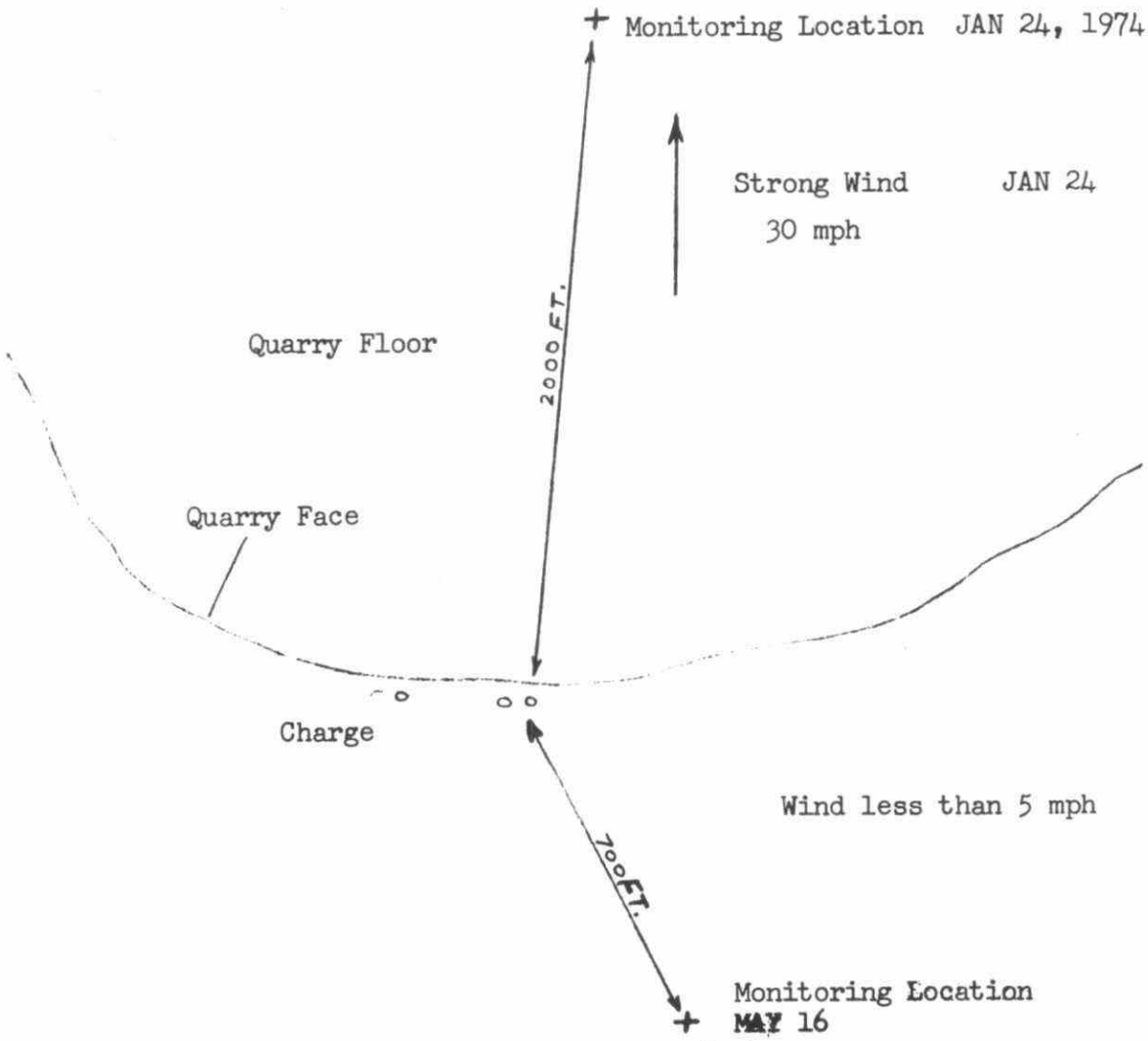


FIG. 26: ANALYSIS SYSTEM



DETAILS OF BLASTS

	JAN 24th	MAY 16th
Distance	2000' in front of face	700' behind face
Number of Holes	12	14
Total Charge	24100 lbs	24100 lbs
Charge/Delay	2008 lbs average	1768 lbs average (1950 lbs max.)
Delays	one 25 ms delay/Hole	plus backup line
Depth of Holes	78 ft.	78 ft.
Stemming Height	16 ft.	16 ft.

FIG. 27: BLASTS AT INDUSMIN QUARRY, ACTON
JAN 24th and MAY 16th, 1974

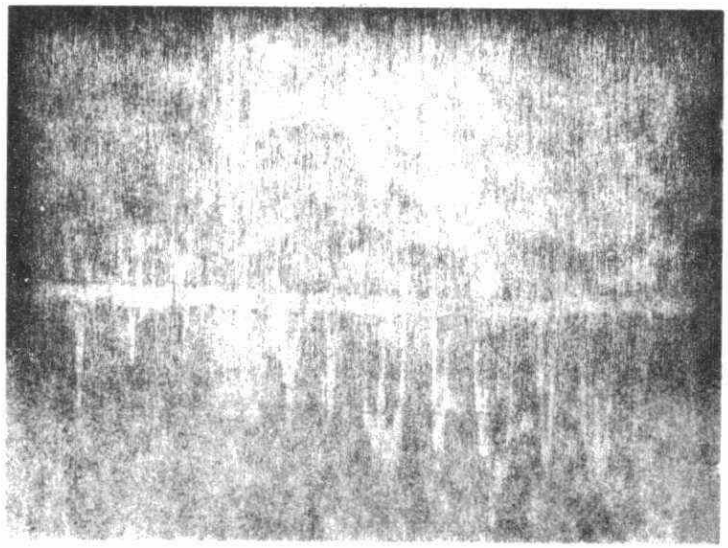


FIG 28 INDUSMIN QUARRY January 24th, 1974
OVERPRESSURE VS. TIME AT 2000 FT.
VERTICAL SCALE 1 PSF/DIV HORIZONTAL SCALE 50 MS/DIV
SONIC BOOM MICROPHONE SYSTEM A

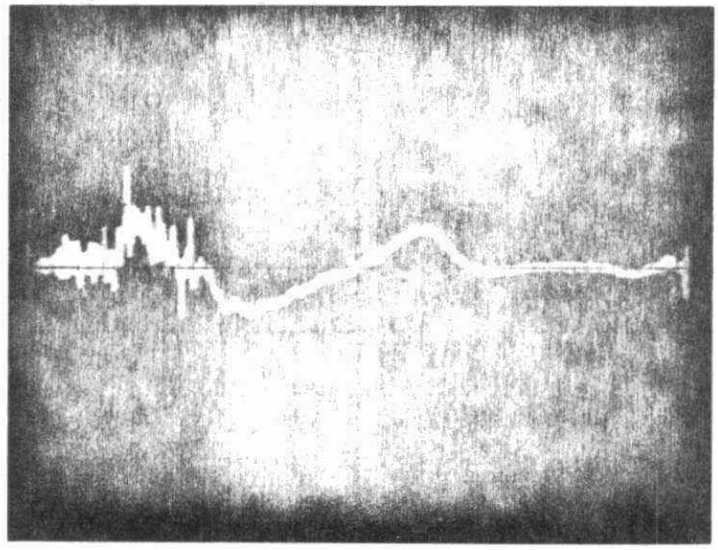


FIG 29a INDUSMIN QUARRY, May 16th, 1974
OVERPRESSURE VS. TIME AT 700 FT.
VERTICAL SCALE 1.78 PSF/DIV HORIZ. SCALE 5/16 S/DIV
PEAK OVERPRESSURE = 2.7 PSF (137 dB)
SONIC BOOM MICROPHONE SYSTEM B

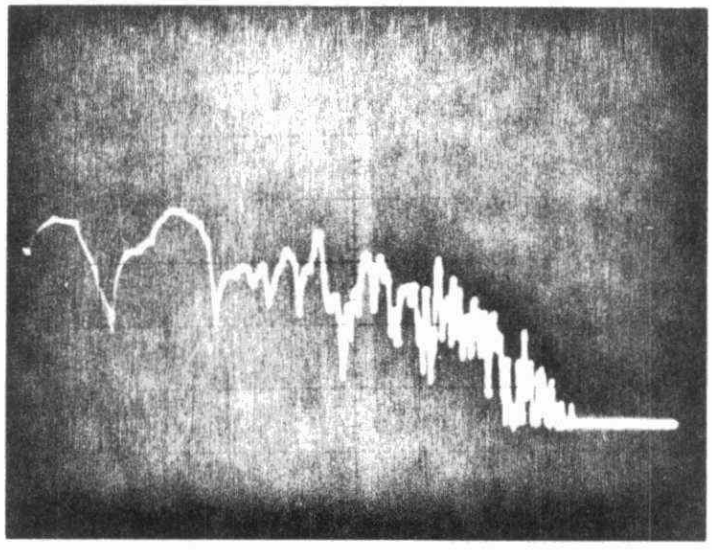


FIG 29b SPECTRUM OF FIG 29a
RELATIVE AMPLITUDE LEVEL (10 dB/ DIV) VS. LOG FREQUENCY
(500 Hz FULL SCALE, 5 DIV/DECADE)

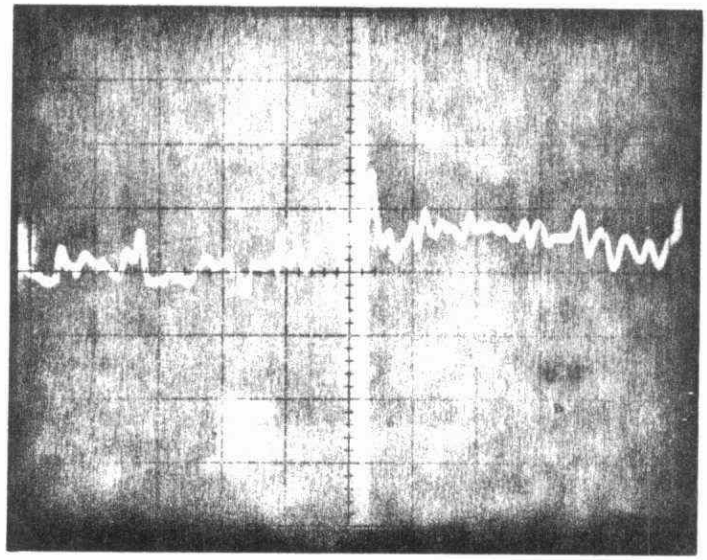


FIG 29c PEAK OF TRACE SHOWN IN FIG 29a
VERT. SCALE 1.78 PSF/DIV HORIZ. SCALE 1/32
S/DIV PEAK OVERPRESSURE = 2.7 PSF (137 dB)

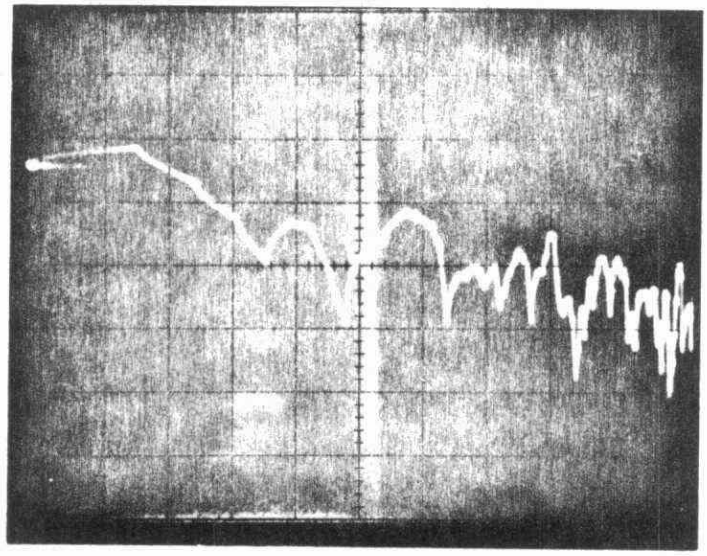
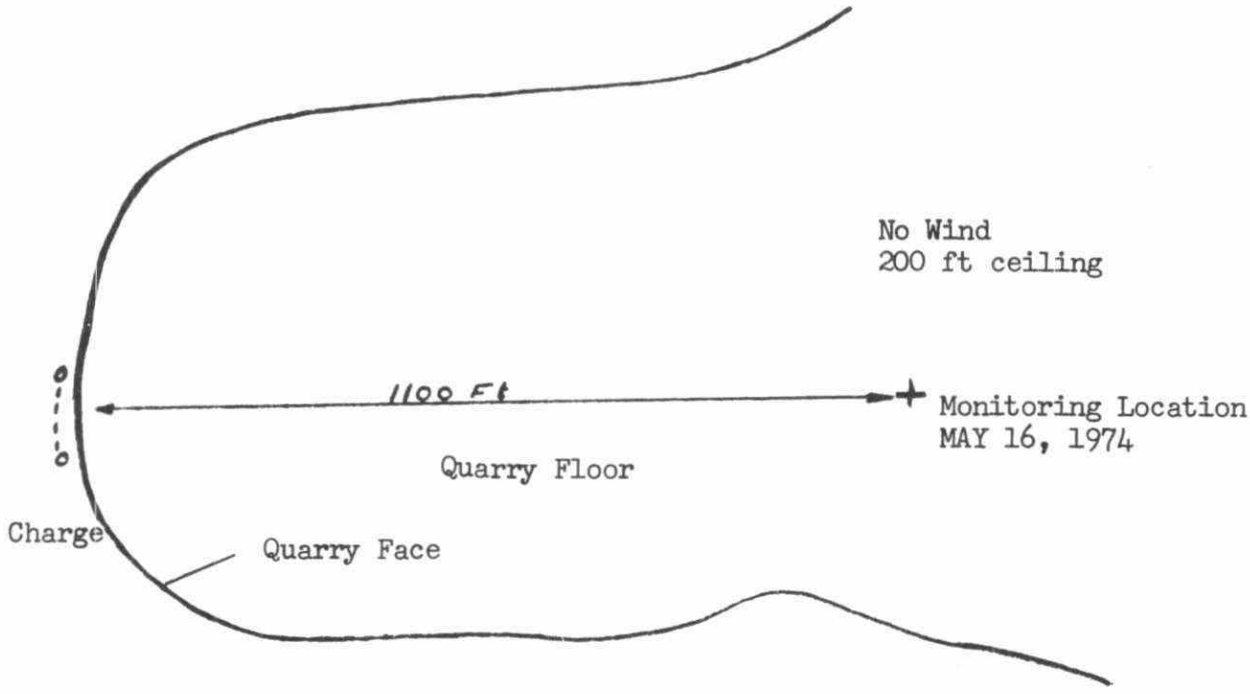


FIG 29d LOW FREQUENCY END OF FIG 29b
(100 Hz FULL SCALE , 5 DIV/DECADE)



DETAILS OF BLASTS

	First Blast	Second Blast
Distance	1100 ft.	1100 ft.
Number of Holes	15	8
Total Charge	9592.5 lbs.	5916 lbs.
Charge/Delay	639.5 lbs.	739.5 lbs.
Delays	one 35 ms delay/hole with 50 ms backup line	
Depth of Holes	65 ft.	75 ft.
Stemming Height	10 ft.	10 ft.

FIG. 30: TWO BLASTS AT MILTON QUARRY
MAY 16, 1974

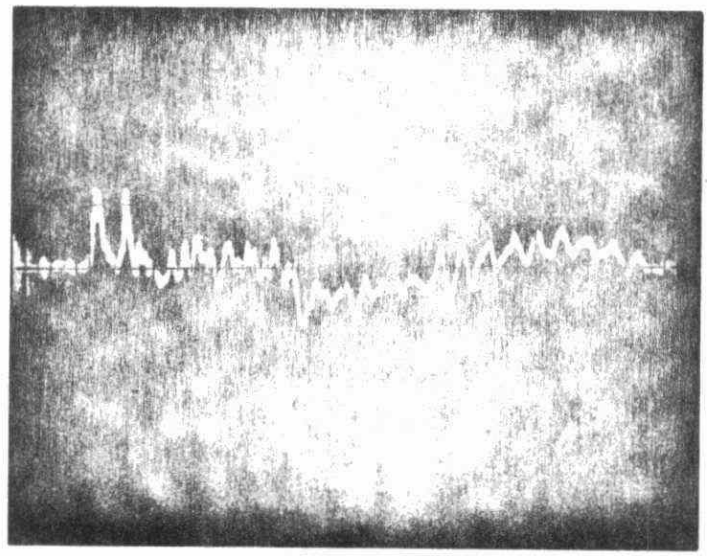


FIG 31a MILTON LIMESTONE, May 16th, 1974
OVERPRESSURE VS. TIME AT 1100 FT.
VERT. SCALE 1.78 PSF/DIV. HORIZ. SCALE 125 MS/DIV
PEAK OVERPRESSURE = 2.0 PSF (134 dB)

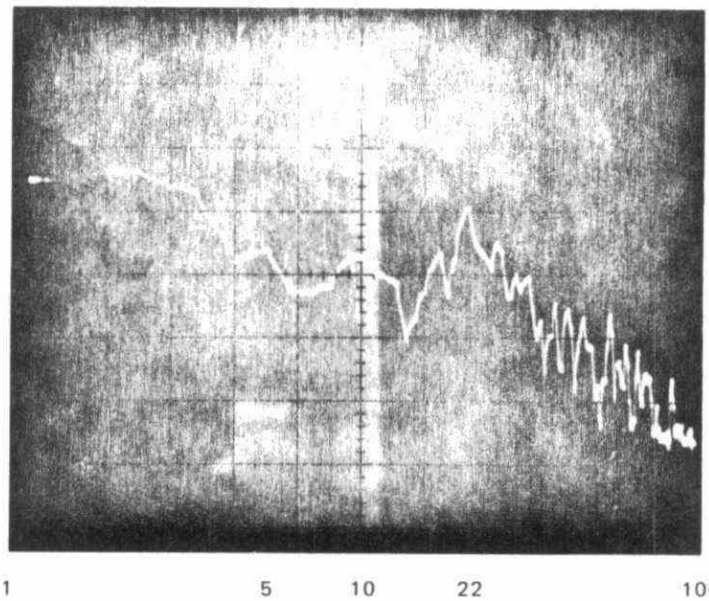


FIG 31b SPECTRUM OF TRACE SHOWN IN FIG 31a
RELATIVE AMPLITUDE LEVEL (10 dB/DIV) VS. LOG FREQUENCY (FULL SCALE 100 Hz, 5 DIV/DECADE)

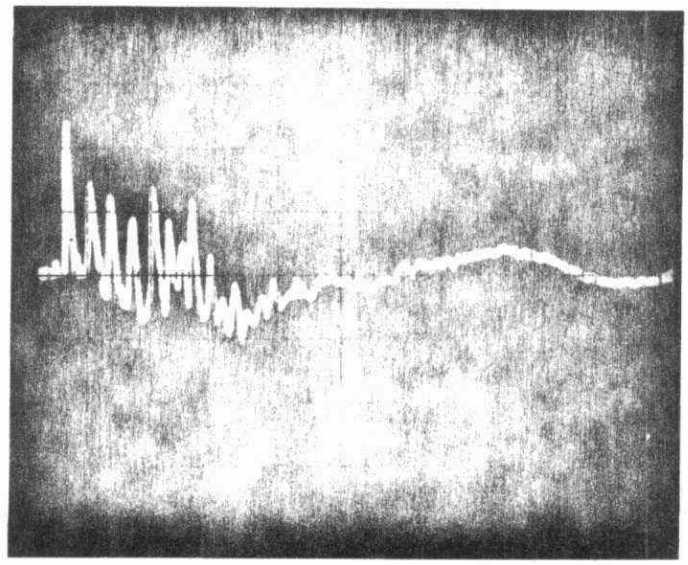


FIG 32a MILTON LIMESTONE, May 16th, 1974
OVERPRESSURE VS. TIME AT 1100 FT.
VERT. SCALE 1.78 PSF/DIV. HORIZ. SCALE 125 MS/DIV
PEAK OVERPRESSURE = 4.0 PSF (140 dB)
SONIC BOOM MICROPHONE - SYSTEM B

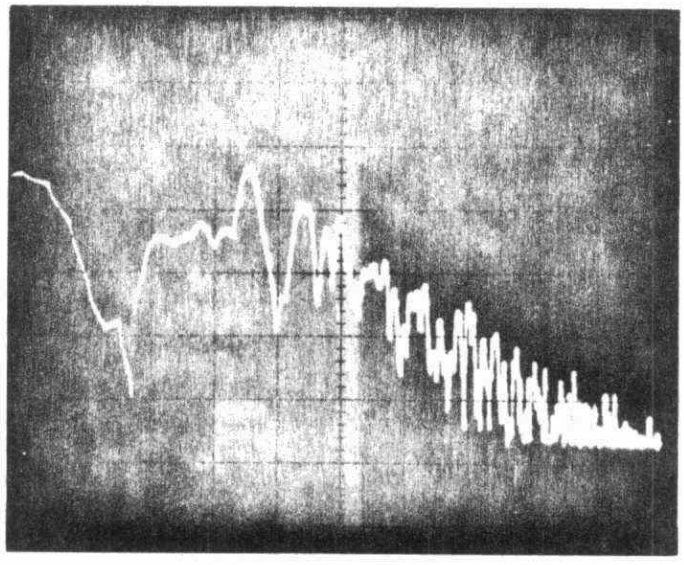
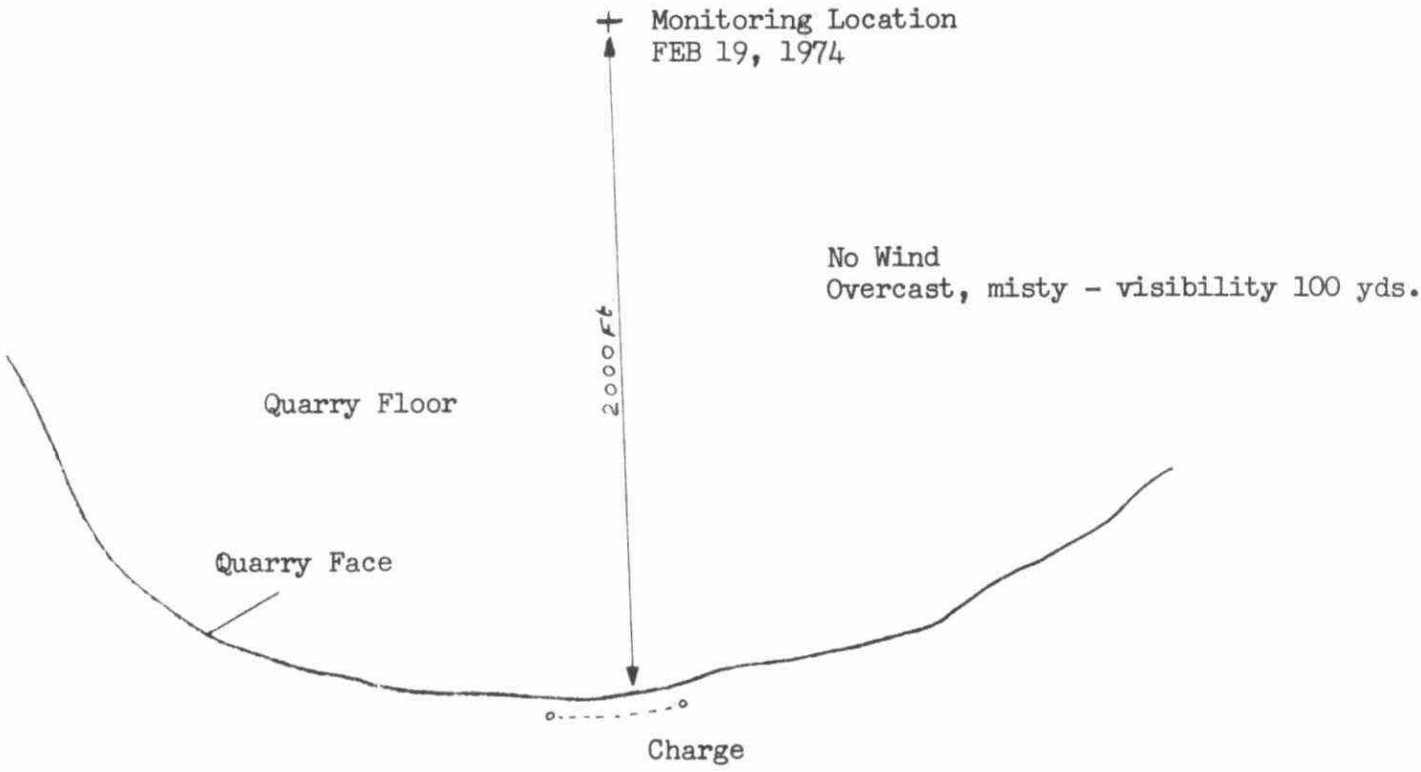


FIG 32b SPECTRUM OF TRACE SHOWN IN FIG 32a
RELATIVE AMPLITUDE LEVEL (10 dB/DIV) VS. LOG FREQUENCY (500 Hz FULL SCALE, 5 DIV/DECADE)



DETAILS OF BLAST

Distance	2000 ft.
Number of Holes	14
Total Charge	27850 lbs.
Maximum Charge/delay	1857 lbs.
Delays	one 25 ms delay/hole
Depth of Holes	81.5 ft.
Stemming Depth	16 ft.

FIG. 33: BLAST AT INDUSMIN QUARRY, ACTON
FEB 19, 1974

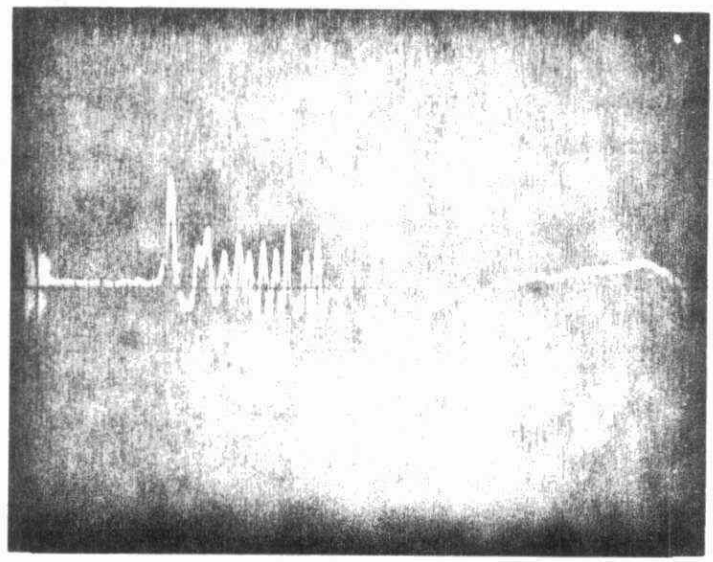


FIG 34a INDUSMIN QUARRY, February 19th, 1974
OVERPRESSURE VS. TIME AT 2000 FT.
VERT. SCALE 1.27 PSF/DIV HORIZ. SCALE 200 MS/DIV
PEAK OVERPRESSURE 2.2 PSF (135 dB)
SONIC BOOM MICROPHONE-SYSTEM B

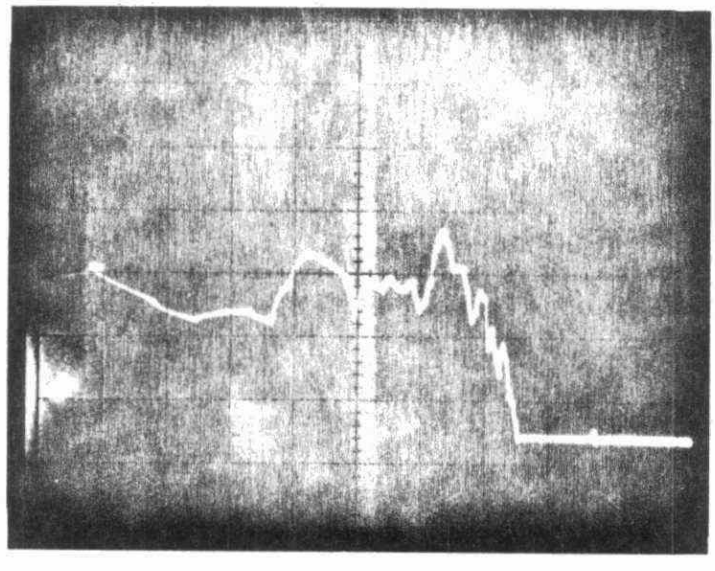


FIG 34b SPECTRUM OF TRACE SHOWN IN FIG 34a
RELATIVE AMPLITUDE LEVEL (10 dB/DIV) VS. LOG
FREQUENCY (5 DIV/DECADE)

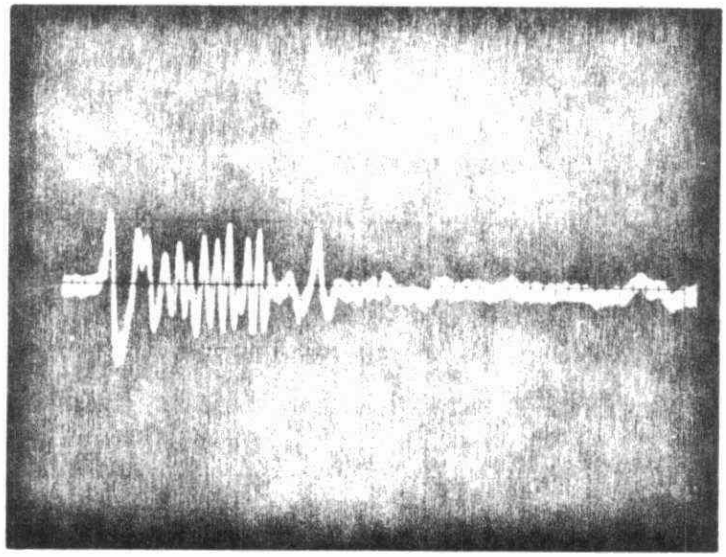


FIG 34c INDUSMIN QUARRY, February 19th, 1974
OVERPRESSURE VS. TIME AT 2000 FT.
VERT. SCALE 1.32 PSF/DIV HORIZ. SCALE 200 MS/DIV
PEAK +VE OVERPRESSURE 1.3 PSF (130 dB)
PEAK -VE OVERPRESSURE 1.6 PSF (132 dB)
B & K 2209 - 4133 - SYSTEM B

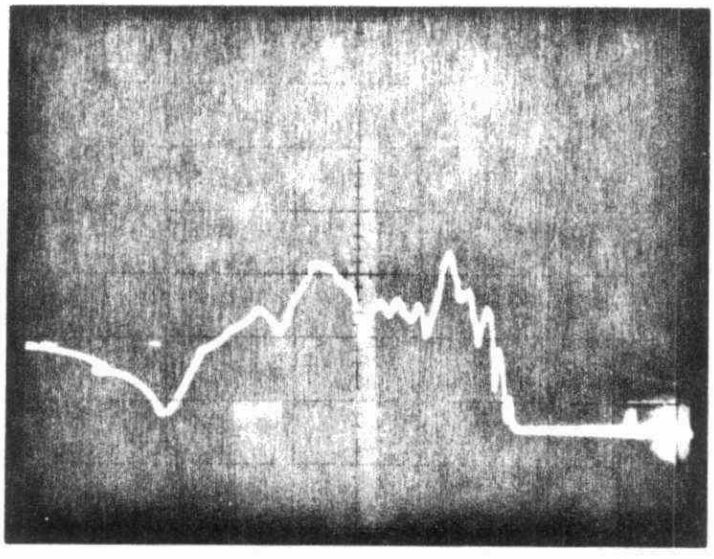
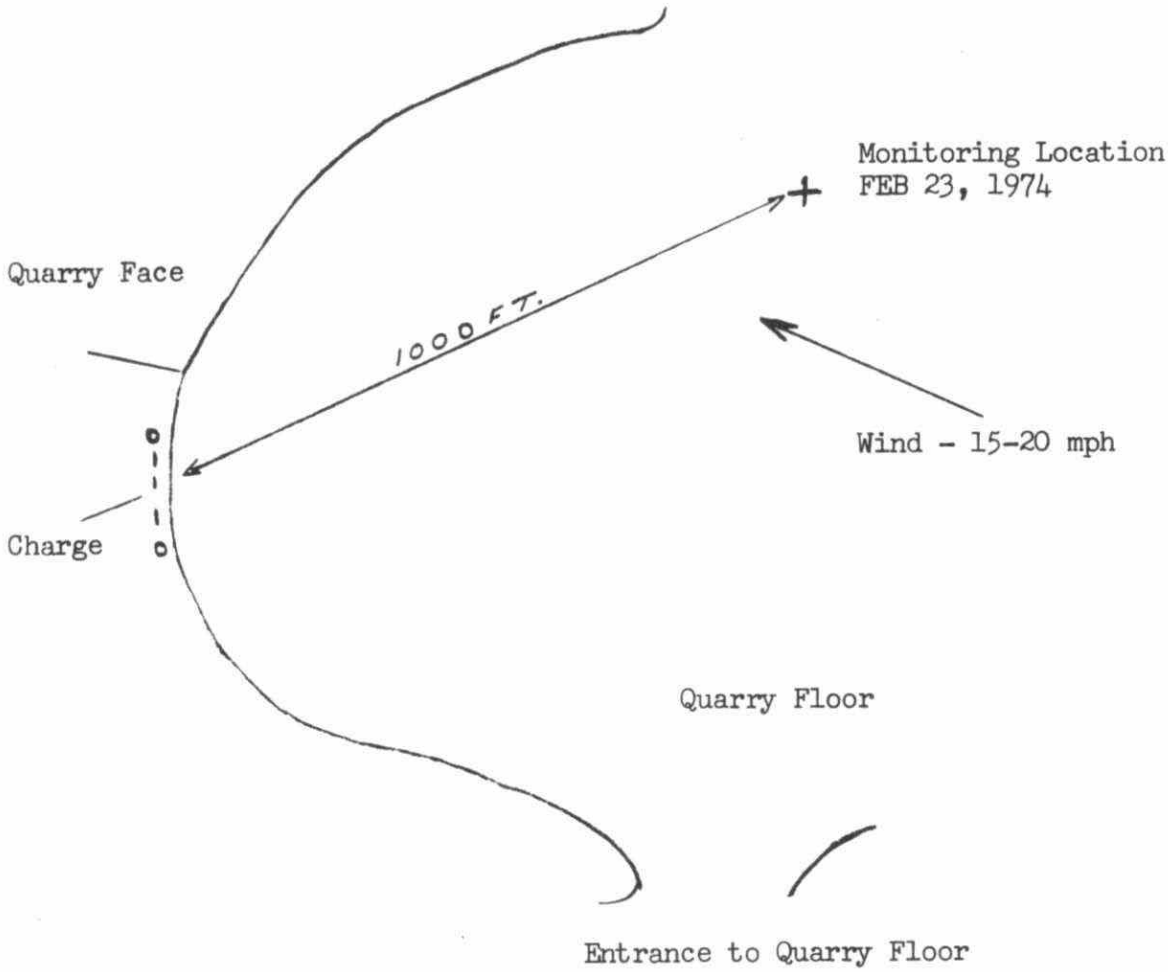


FIG 34d SPECTRUM OF TRACE SHOWN IN FIG 34c
RELATIVE AMPLITUDE LEVEL (10 dB/DIV) VS. LOG FREQUENCY (5 DIV/DECADE)



DETAILS OF BLAST

Distance	1000 ft. (in front of face)
Number of Holes	14
Total Charge	14700 lbs.
Charge/Delay	1050 lbs.
Delays	one 25 ms/hole
Depth of Holes	100 ft.
Stemming Height	12 ft.

FIG. 35: BLAST AT DUFFERIN QUARRY, MILTON
FEB 23, 1974

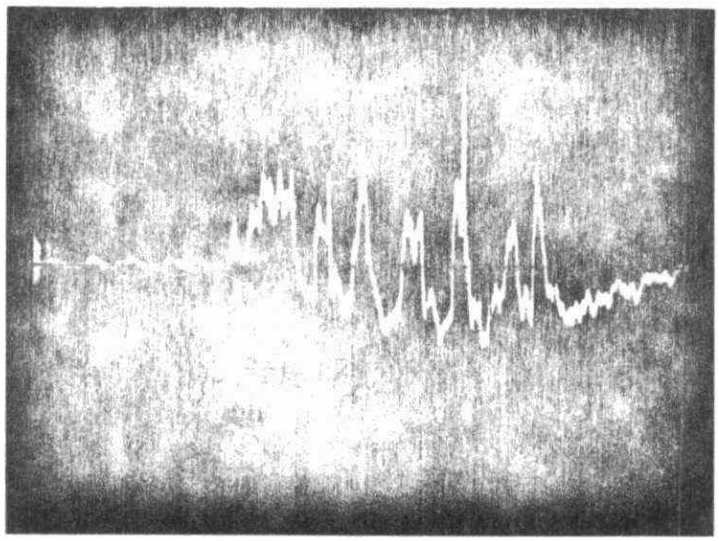


FIG 36a DUFFERIN QUARRY, February 23rd, 1974
OVERPRESSURE VS. TIME AT 1000 FT.
VERT. SCALE 1.42 PSF/DIV HORIZ. SCALE 125 MS/DIV
PEAK OVERPRESSURE 4.0 PSF (140 dB)
SONIC BOOM MICROPHONE - SYSTEM B

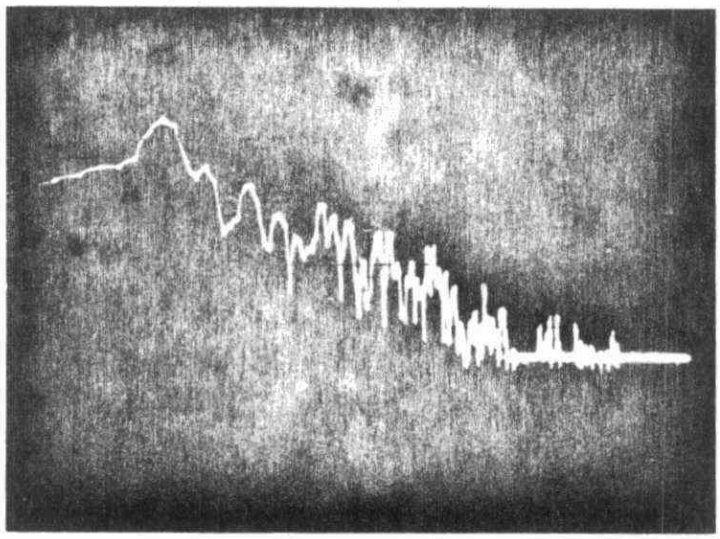


FIG 36b SPECTRUM OF TRACE SHOWN IN FIG 36a
RELATIVE AMPLITUDE LEVEL (10 dB/DIV) VS.
LOG. FREQUENCY (FULL SCALE 500 Hz, 5 DIV/DECADE)

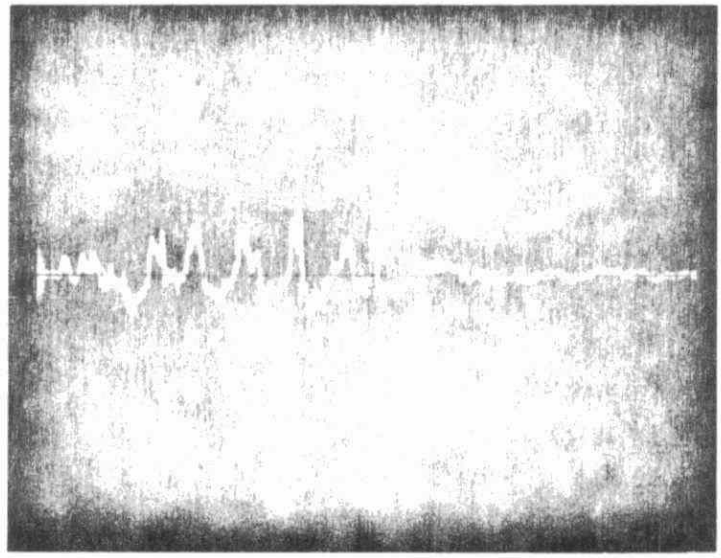
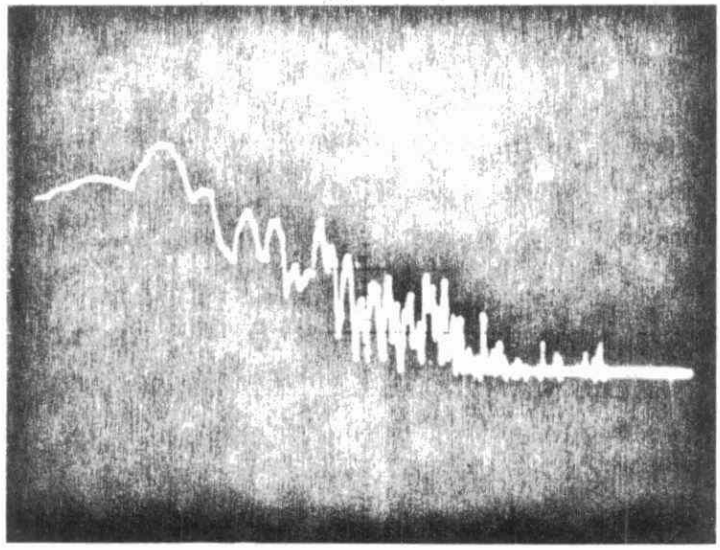
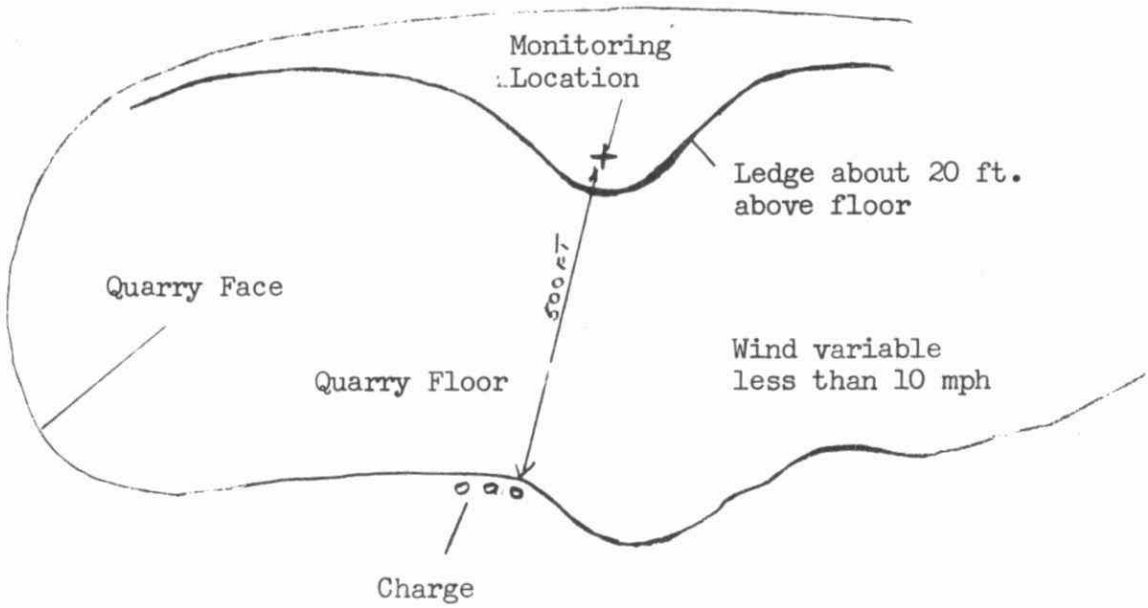


FIG 36c DUFFERIN QUARRY, February 23rd, 1974
OVERPRESSURE VS. TIME AT 1000 FT.
VERT. SCALE 3.15 PSF/DIV HORIZ. SCALE
125 MS/DIV B & K 2209 - 4133 - SYSTEM B



IG 36d SPECTRUM OF TRACE SHOWN IN FIG 36c
RELATIVE AMPLITUDE LEVEL (10 dB/DIV) VS. LOG
FREQUENCY (FULL SCALE 500 Hz, 5 DIV/DECADE)



DETAILS OF BLAST

Distance	500 ft.
Number of Holes	3
Total Charge	225 lbs.
Charge/Delay	25 lbs.
Delays	Three 25 ms delays/hole
Depth of Holes	40 ft.
Stemming Height	3 ft.

FIG. 37: BLAST AT TORONTO BRICK
FEB 14, 1974

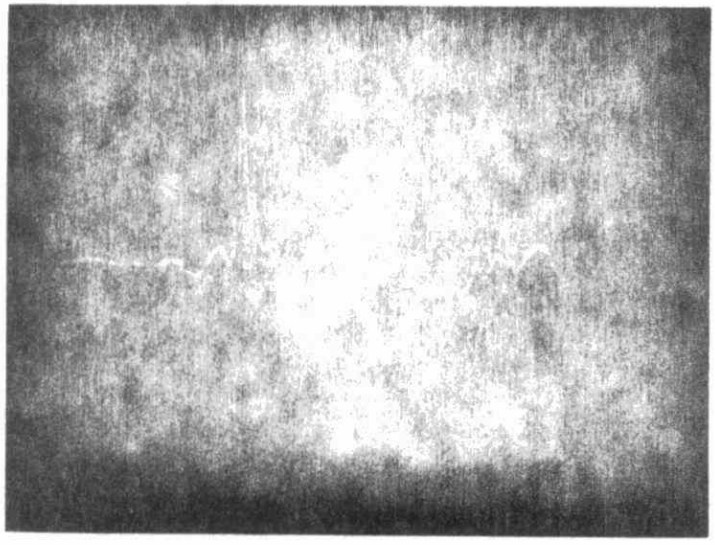


FIG 38a TORONTO BRICK QUARRY, February 14th, 1974
OVERPRESSURE VS. TIME AT 500 FT.
VERT. SCALE 0.22 PSF/DIV. HORIZ SCALE 20 MS/DIV
PEAK OVERPRESSURE = 0.6 PSF (123 dB)
B & K 2204 - 4145 SYSTEM B

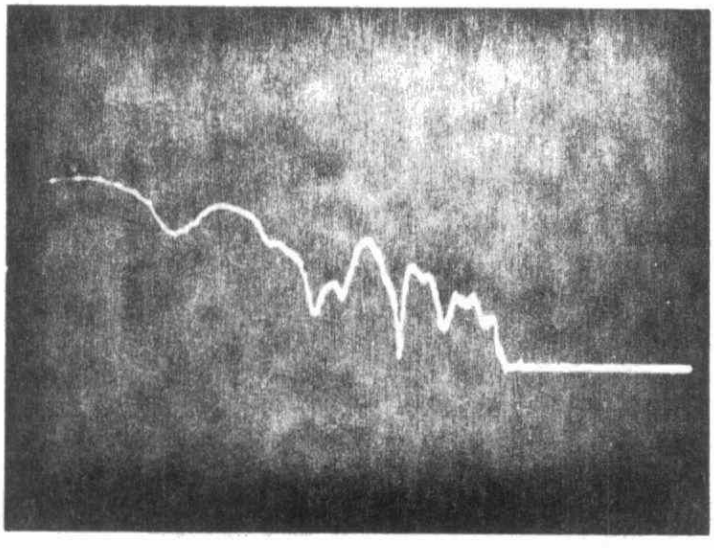
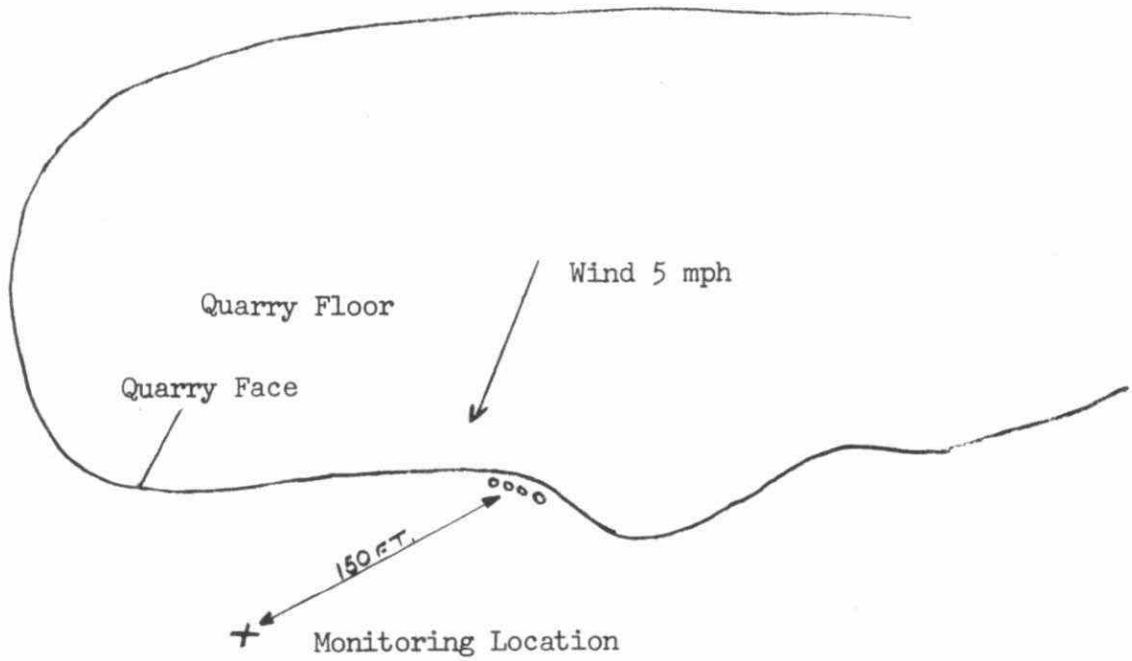


FIG 38b SPECTRUM OF TRACE SHOWN IN FIG 38a
RELATIVE AMPLITUDE LEVEL (10 dB/DIV) VS. LOG
FREQUENCY (FULL SCALE 1 KHz, 5 DIV/DECADE)



DETAILS OF BLAST

Distance	150 ft.
Number of Holes	4
Total Charge	102 lbs.
Charge/Delay	8.5 lbs.
Delays	Three 25 ms delay/hole
Depth of Holes	45 ft.
Stemming Height	3 ft.

FIG. 39: BLAST AT TORONTO BRICK
MAY 14, 1974

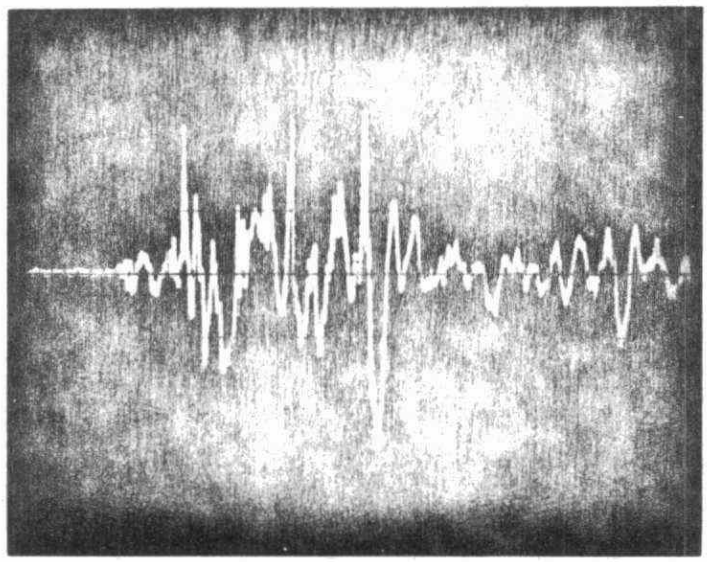


FIG 40a TORONTO BRICK QUARRY, May 14th, 1974
OVERPRESSURE VS. TIME AT 150 FT.
VERT. SCALE 0.15 PSF/DIV.
HORIZ. SCALE 125 MS/DIV
B & K 2204 - 4145 SYSTEM B

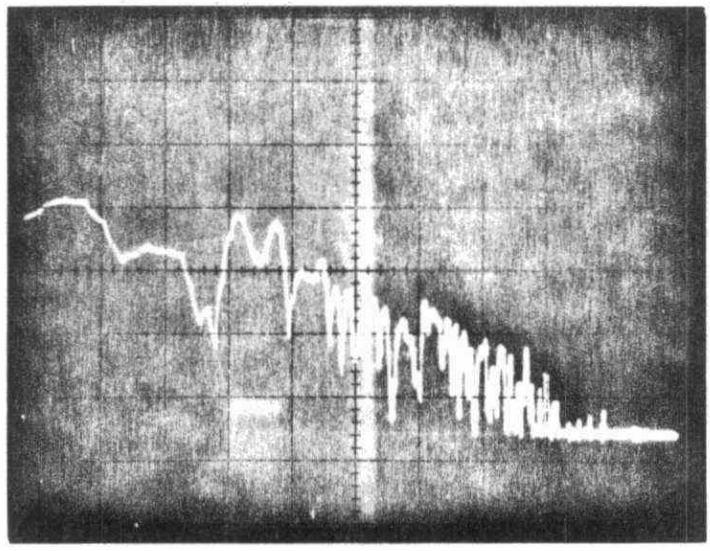


FIG 40b SPECTRUM OF TRACE SHOWN IN FIG 40a
RELATIVE AMPLITUDE LEVEL (10 dB/DIV) VS.
LOG. FREQUENCY (FULL SCALE 500 Hz, 5 DIV/DECADE)

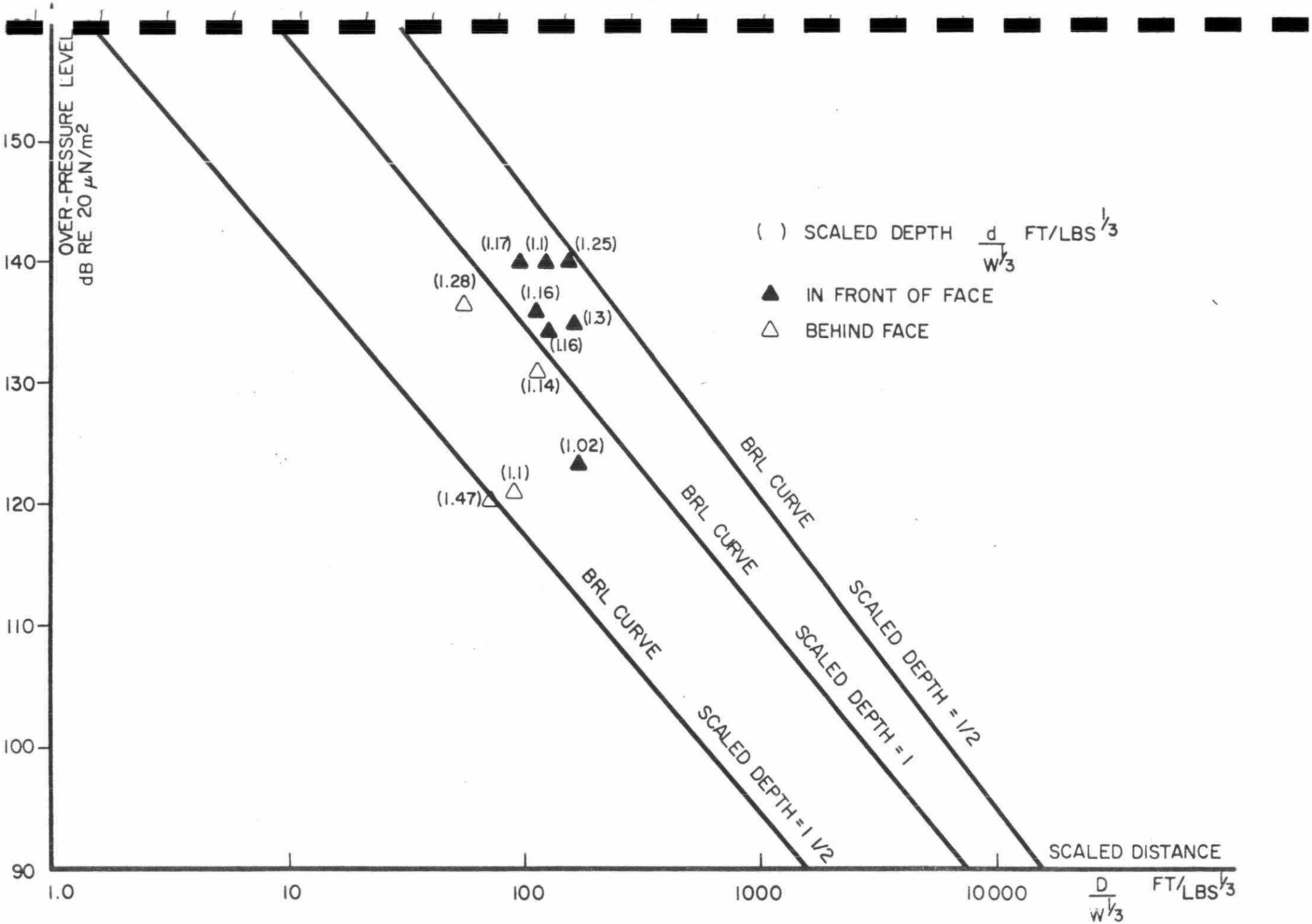


FIG. 41: MEASURED DATA.
OVERPRESSURE VS. SCALED DISTANCE

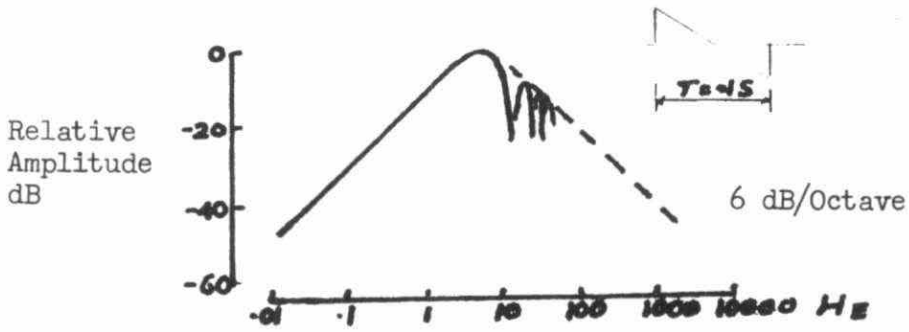


FIG 42 CHARACTERISTIC SPECTRUM OF IDEAL N - WAVE SONIC BOOM (9)

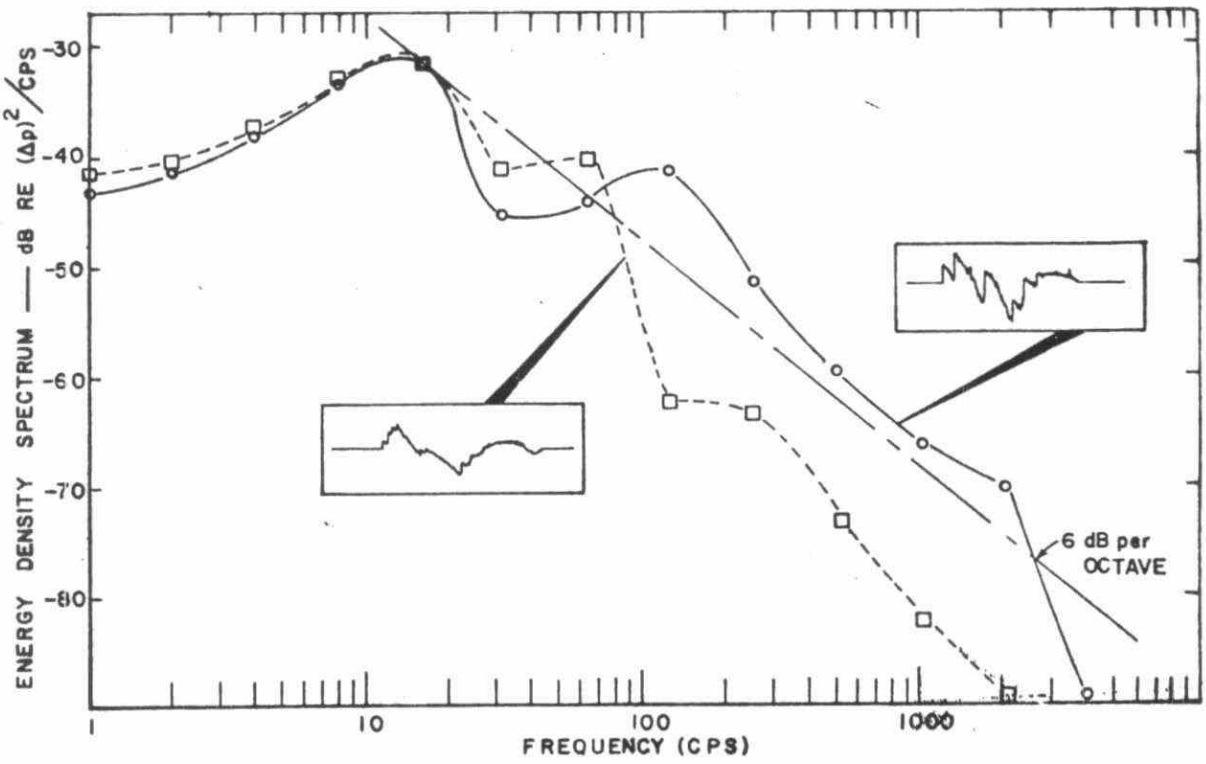


FIG 43 SPECTRA OF TWO MINIMUM ALTITUDE SONIC BOOMS OF THE SAME PEAK OVERPRESSURE AT THE SAME LOCATION UNDER IDENTICAL FLIGHT CONDITIONS (9)

TABLES

Building Designation	Charge (lb)	Distance (ft)	Air Blast Pressure (lb per square foot
R	47	215	1.25
R	120	44	2.5
Church	No records	-	-
E	260	80	1
E	140	55	12
School	750	100	2
T13	15	-	-
14	31	-	-
15	250	-	-
		120+	
16	50	150	5
17	350	100	12
18	600	80	25

TABLE 1: AIR BLAST OBSERVATIONS (3)

Boom dates	Metro-politan population	Total SS over-flights	Median peak over-pressure N/m^2	Median peak over-pressure lb/ft^2	Boom-person ex-posures (millions)	Number of com-plaints	Number of claims filed	Number of claims paid	Value of claims paid
St. Louis, 1961-62	*2,600,000	150	86	1.8	390.0	5,000	1,624	825	$58,648
Oklahoma City, 1964	†512,000	1,253	58	1.2	642.0	15,452	4,901	289	123,061
Chicago, 1965	6,221,000	49	86	1.8	304.5	7,116	2,964	1,442	114,763
Total	9,333,000	1,452	††84	1.76	1,336.5	27,568	9,489	2,556	$296,472

*Metropolitan area as given in National Geographic Atlas, 1963 edition, rounded off to nearest thousand population.

†Greater St. Louis population affected by boom.

††Average.

TABLE 2a SONIC BOOM DAMAGE DATA (5)

	Complaints per million BPE	Claims per million BPE	Paid-out claims per million BPE	Paid-out damage per million BPE
St. Louis	12.8	4.16	2.11	$151
Oklahoma City	24.1	7.63	.45	192
Chicago	23.4	9.75	4.74	377
Weighted average	20.6	7.10	1.91	$ 222

TABLE 2b ANALYSIS OF DAMAGE DATA (5)

Event No.	Characteristic overpressure N/m²	lbf/ft²	Number of additional damages to panes
1	86	1.8	8
2	48	1.0	11
3	96	2.0	80
4	62	1.3	79
5	81	1.7	20
6	86	1.8	11
7	96	2.0	7
8	148	3.1	15
9	200	4.2	8

TABLE 3 HISTORY OF DAMAGE TO GLASS IN GREENHOUSES (8)

Cause of excitation	Element of structure			
	Bell tower	Walls	Roofs	Vaulting
Bell ringing	0.5 to 10		0.3 to 3	0.04 to 0.5
Organ playing		0.01 to 0.2	0.8 to 1	0.01 to 0.5
Road traffic		0.01 to 0.4	0.1 to 0.9	0.02 to 0.6
Sonic bang (predicted)	3 to 10	0.01	20 to 70	1 to 5

TABLE 4 RANGE OF MEASURED RESPONSE AS TYPIFIED BY THE PEAK VIBRATIONAL VELOCITY (MM/SEC) (8)

Cause of excitation	Response
Bell ringing	0.01 to 0.3
Organ playing	0.01 to 0.5
Road traffic	0.01 to 0.4
Sonic bang (predicted)	0.2 to 10

TABLE 5 RANGE OF MEASURED RESPONSE OF WINDOWS AS TYPIFIED BY THE PEAK VIBRATIONAL ACCELERATION (g) (8)

Gauge position	Flight no.	First N-wave		Second N-wave	
		First shock	Second shock	First shock	Second shock
House wall (Great Staughton)	1	4·6	4·8	0·4	0·8
	2	3·2	3·5	0·3	0·8
	3	2·0	2·3	Gauge failed	
	4	—	—	—	—
	5	—	—	—	—
On ground (Great Staughton)	1	4·2	4·6	0·4	0·8
	2	3·2	3·4	0·3	0·8
	3	2·3	2·7	1·2	1·8
	4	nil	nil	nil	nil
	5	1·9	2·3	0·4	1·1

TABLE 6 SONIC BOOM PRESSURES FROM OSCILLOGRAPH RECORDS (PEAK PRESSURES IN PSF MEASURED ON A SHOCK REFLECTING SURFACE) (9)

Gauge position	Flight no.				
	1	2	3	4	5
1 (on ground)	1·9	2·1			
2 (on ground)	—	—			
3 (on ground)	4·0	4·0			
4 (on ground)	4·0	2·0			
5 (on ground)	1·9	1·6	nil	nil	—
6 (on ground)	3·6	3·9	nil	nil	3·1
7 (on ground)			nil	nil	4·6
8 (on ground)			nil	nil	4·1
9 (on ground)			nil	nil	2·8

TABLE 7 SONIC BOOM PRESSURES FROM DIRECT - READING METERS (PEAK PRESSURES IN PSF), FIRST PEAK ONLY OF N-WAVE (9)

Position	Flight no.			
	1	2	3	5
1. Slate roof, facing boom	0·6	0·47		
2. Slate roof, facing boom	0·8	0·8		
3. Slate roof, facing boom	0·9	1·0	±0·46 −0·36	±0·42 −0·36
4. Slate roof, facing boom	0·5	0·6		
5. House wall, facing boom	—	—	—	+0·018 −0·032
6. House wall, gable end	0·07	0·1		
7. Slate roof, away from boom	0·3	0·3	+0·14 −0·14	+0·18 −0·19
8. Tiled roof, facing boom	0·4	0·27		
9. Tiled roof, facing boom	0·6	0·3	+0·20 −0·14	+0·18 −0·18
10. Tiled roof, facing boom	0·5	0·4		
11. Lintel over window	0·1	0·07	+0·04 −0·05	+0·05 −0·05

TABLE 8 HOUSE VIBRATION MEASUREMENTS, PEAK ACCELERATION (UNITS OF g) (9)

	Anticipated typical sonic boom measured (lb/sq ft)[b]		PNdB values from subsonic jet aircraft that would be judged equally acceptable				Typical PNdB values actually present 1.5 miles from airport after takeoff of subsonic jet aircraft	
	Outdoors	Indoors	Outdoors	Indoors			Outdoors	Indoors
				No Rattle	Rattle			
Under flightpath	2.3	0.5	95.5	84.5	98	98[a]	112	95
±4 miles to side of flightpath	2.0	0.45	94.5	83.5	97	97[a]	70	55
±8 miles to side of flightpath	1.6	0.36	92.5	81.5	95	95[a]	...	...

[a] Broadbent and Robinson.[8] [b] Anticipated for an intercontinental SST during transonic climb.

TABLE 9 RESULTS OF TEST OF SUBJECTIVE ACCEPTIBILITY OF SUBSONIC JET AIRCRAFT AND SIMULATED SONIC BOOMS (11)

Distance	Overpressure (lb/sq ft) for				
	B-58 at an altitude of				F-106 at an altitude of
(miles)	46 000 ft	41 000 ft	36 000 ft	31 000 ft	41 000 ft
0–2	1.6	1.8	2.3	2.7	1.3
2–4	1.5	1.7	2.1	2.4	1.2
4–6	1.3	1.6	1.8	2.1	1.1
6–8	1.2	1.4	1.5	1.6	1.0
8–10	1.1	1.2	1.2	1.2	0.8
10–12	1.0	0.9	0.8	0.8	0.6
12–14	0.9	0.7	0.6	0.4	0.4
14–16	0.8	0.6	0.4	0.2	0.3

TABLE 10 ESTIMATED SONIC BOOM GROUND OVERPRESSURE AS A FUNCTION OF DISTANCE FROM GROUND TRACK (4)

Nature of Interferences Reported	Percentage of Total Interviewed who Reported:	
	Interference	Annoyance
House shaking	93	38
Startled	74	31
Sleep interrupted	42	22
Rest and relaxation interrupted	24	16
Conversation interrupted	22	10
Radio and television interrupted	14	6

TABLE 11 PERCENTAGE OF 1145 INTERVIEWED IN THE ST. LOUIS AREA WHO REPORTED VARIOUS INTERFERENCES DUE TO SONIC BOOMS AND RESULTING ANNOYANCE (4)

Sound Overpressure (lb/ft²)	(dyn/cm²)	Predicted Effects
0–1	0–478	No damage to ground structures; no significant public reaction, day or night.
1.0–1.5	478–717	No damage to ground structures; probable public reaction.
1.5–1.75	717–837	No damage to ground structures; significant public reaction particularly at night.
1.75–2.0	837–957	No damage to ground structures; significant public reation.
2.0–3.0	957–1435	Incipient damage.

TABLE 12 ESTIMATED EFFECTS OF SONIC BOOM ON STRUCTURES AND PEOPLE (4)

Activity	Particle velocity in room			Particle velocity in adjacent room		
	Radial in/sec	Vertical in/sec	Transverse in/sec	Radial in/sec	Vertical in/sec	Transverse in/sec
Walking	0.00914	0.187	0.372	0.00129	.....	0.00102
	....	.0578	.0155	.00167	0.0281	.00227
	.....	.00770	.00210	.00229	.0626	.00462
	.0600	.120	.0300	.....	.....	.....
	.0100	.0600	.007	.....	.....	.....
	.00600	.0110	.00400	.....	.....	.....
	.00800	.0200	.00700	.....	.....	.....
Door closing	.0110	.0558	.0149	.00170	.....	.00153
	.....	.0150	.00500	.0125	.0970	.00963
	.008	.0100	.00800	.....	.....	.....
Jumping	.0524	4.03	1.05	.120	.219	.551
	.120	.219	.551	.0153	.0239	.0101
	1.00	2.500	1.70	.00450	.0100	.0045
	.500	5.00	1.10	.....	.....	.....
Automatic washer	.00340	.00400	.00340	.....	.....	.....
Clothes dryer	.00500	.00500	.00500	.....	.....	.....
Heel drops	.0100	.0100	.0100	.....	.....	.....
	.0800	.600	.0300	.....	.....	.....
	.0200	.200	.0200	.006	.0100	.006
	.900	3.500	.400	.....	.....	.....
	.0500	.450	.0700	.009	.014	.008
	.0100	.200	.00900	.....	.....	.....

TABLE 13 VIBRATION FROM NORMAL ACTIVITIES (2)

TEST		TOTAL CHARGE LBS	CHARGE/ DELAY LBS	DISTANCE D Ft.	STEMMING HEIGHT d Ft.	PEAK OVER-PRESSURE psf/dB	DURATION secs
INDUSMIN.	Jan. 24	24100	2008	2000	16	greater than 4.0/140	
INDUSMIN.	Feb. 19	27850	1857	2000	16	2.2/135	1.0
INDUSMIN.	May 16	24750	1950	700	16	2.7/137	2.0
DUFFERIN.	Jan. 29	11000	1100	1150	12	2.5/136	
DUFFERIN.	Feb. 23	14700	1050	1000	12	4.0/140	0.9
DUFFERIN.	May 15	26000	1300	1000	12	0.45/121	2.7
MILTON.	Nov. 14	6685	668.5	1000	10	1.4/131	
MILTON.	May 16	9592.5	639.5	1100	10	2.0/134	1.1
MILTON,	May 16	5916	739.5	1100	10	4.0/140	0.5
TORONTO.	Feb. 14	225	25	500	3	0.6/123	0.14
TORONTO.	May 14	102	8.5	150	3	0.42/120	1.1

TABLE 14: SUMMARY OF MEASUREMENTS IN THIS STUDY

TD
893.6
.Q35
T39